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Engineering Assessment of the Potential Impact of Federal Radiation Protection Guidance on the AM, FM, and TV Broadcast Services

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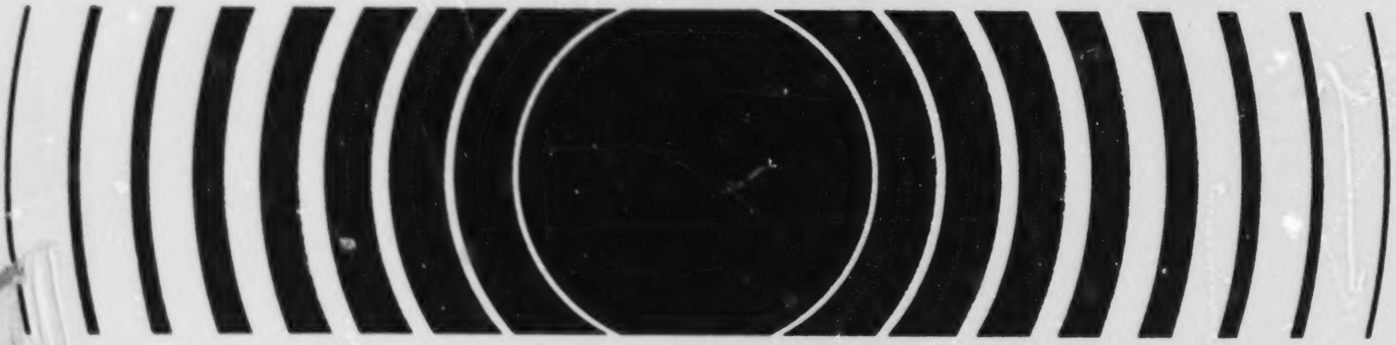

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ii

ABSTRACT

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An Engineering Assessment of the Potential Impact of Federal Radiation Protection Guidance on the AM, FM, and TV Broadcast Services

1. Introduction

This report describes an engineering analysis of potential impact of proposed EPA Federal Radiation Protection Guidance for radiofrequency radiation on the broadcast industry. The task of assigning costs to this impact has been undertaken by Lawrence Livermore National Laboratory (LLNL) under an interagency agreement with EPA through the Department of Energy. It was decided at the beginning of this study that EPA was best prepared to perform the engineering analysis because of its knowledge and experience with broadcast radiating systems. EPA has examined these systems through measurements, theoretical predictions, and computer modeling for over ten years.

EPA's objective in this study was to develop the most accurate estimate of impact to industry practical with available information. A completely individualized examination of each broadcast source was not possible since there are currently more that 10,000 such sources in operation in the United States.

Limited information about each source is available in computerized data bases maintained by the Federal Communications Commission (FCC). EPA obtained these data bases and augmented them by manually extracting additional information from the FCC written files in Washington, D.C. Computer models were developed which combined theoretical methods and measured antenna patterns to accurately predict the fields produced near broadcast antennas. The models were field tested for accuracy and then applied to the augmented data bases. The results indicate, for eighteen hypothetical guidance levels, the numbers of stations predicted to exceed the guidance as well as the numbers that could be brought into compliance using various "fixes". These numbers were provided to LLNL for determination of the total societal costs and costs to industry that would be associated with implementation of the proposed guidance [1].

2. Data Bases

The data on each station used in this study were taken from FCC files. The FCC maintains records of each station on magnetic tape which is provided in updated form to EPA every six months. These computer files are referred to as the AM, FM, and TV Engineering Data Bases. The tape records contain all the required information on AM stations for EPA's AM model, but only part of the information necessary for the FM and TV models. Consequently, manual augmentation of these files was necessary.

Because EPA's measurement experience indicated that the FM radio service tends to contribute most to publicly accessible high intensity exposures, the greatest effort was expended treating near-in (close proximity) propagation models of FM radio stations. The FCC FM automated records do not contain the tower height above ground, type of antenna, or number of bays in the antenna used to transmit the signal. These parameters are critical for proper modeling of each facility. A graduate student in the Washington, D.C. area was hired to manually extract this information from the FCC files during the summer of 1980. These data were later combined with the existing magnetic tape records to produce an adequate data base for FM stations. The final version of the data base contained a combination of 1980 and 1982 data.

Although there were 4,374 FM stations in operation at the time of this study, the student was only able to extract the additional required information on 3,895 of these facilities during his appointment. All modeling was performed on these 3,895 stations with the assumption that the results represented (3,895/4,374) X 100 per cent of the total impact on FM stations.

A less detailed propagation model was used for predicting fields produced by TV stations and therefore less information on each facility was required. The magnetic tape records from FCC contained all the necessary information for modeling except tower height above ground and aural ERP. This missing information was manually extracted from the 1982-1983 TV Factbook [2], a commercial publication containing certain information about TV stations taken from the FCC files. The Factbook information was merged with the January 1983 FCC automated TV Engineering Data Base to produce the final data base used in modeling TV stations. The automated FCC AM file used in this study was also the January 1983 version.

3. Guidance Levels

Since the final values at which the Guidance will be set were not known at the time of this study, all analyses were performed for 18 alternative guidance levels. This approach has the advantage of revealing the variations in impact as a function of guidance level.

The 18 guidance levels each differ for AM and FM frequencies. This frequency dependence reflects the general shape assumed by existing radiofrequency standards in the United States and other countries and provides an approximation to the shape which will probably be proposed by EPA. Figure 1 shows one possible shape and set of limiting values for guidance level 6. Note that the curve is flat from 30 MHz to 1 GHz. Many existing standards begin an upward ramp at about 300 MHz. EPA's proposed guidance may also incorporate a ramp, but the exact shape was not established before this study. The shape which was chosen for this study, as shown in Figure 1, represents the most conservative approach which might be chosen by EPA. If a portion of the flat region which extends from 30 MHz to 1 GHz were changed to a ramp shape, the resulting impact of the guidance on UHF stations would be reduced from the values predicted in this analysis. The limiting exposure values assigned to the 18 alternative guidance levels for AM, FM, and TV frequencies are shown in Table 1.

The results of this impact analysis can be used even if a different shape is proposed. Figure 2 shows another possible shape and set of limiting exposure values for the guidance. The total impact for this case could be found by combining the guidance level 6 (see Table 1) impact for FM and VHF-TV stations, the guidance level 9 impact for AM stations, and the guidance level 6 or 7 impact for UHF-TV stations. The UHF-TV band extends from 470-806 MHz which would correspond to guidance levels of 157-269 $\mu W/cm^2$ for the guidance curve shown in Figure 2. Thus, guidance level 6 (100 $\mu W/cm^2$) would overestimate impact while guidance level 7 (200 $\mu W/cm^2$) would probably estimate the actual impact more accurately. The range of alternative guidance

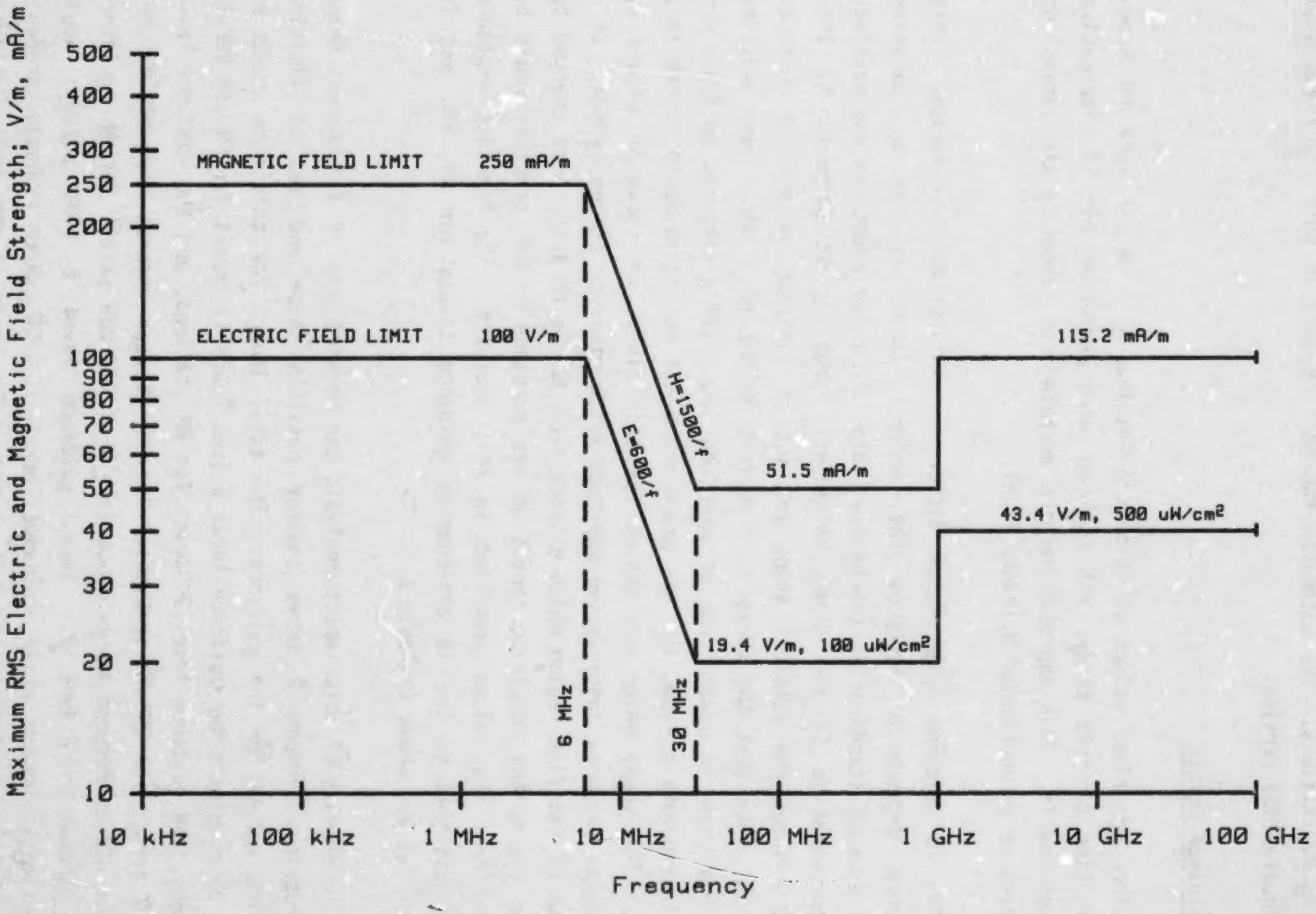

FIGURE 1. Limiting values of field stength for guidance level 6

TABLE 1. LIMITING VALUES OF THE 18 GUIDANCE LEVELS FOR AM, FM, AND TV FREQUENCIES

Guidance Level No.	Limiting Field Strength at AM Frequencies	Limiting Power Densities at FM and TV Frequencies
1	10.0 V/m	1 μW/cm^2
2	31.6	10
3	44.7	20
4	70.8	50
5	86.6	75
6	100.0	100
7	141.3	200
8	173.2	300
9	200.0	400
10	223.9	500
11	244.9	600
12	264.6	700
13	281.8	800
14	300.0	900
15	316.2	1,000
16	446.7	2,000
17	708.0	5,000
18	1,000.0	10,000

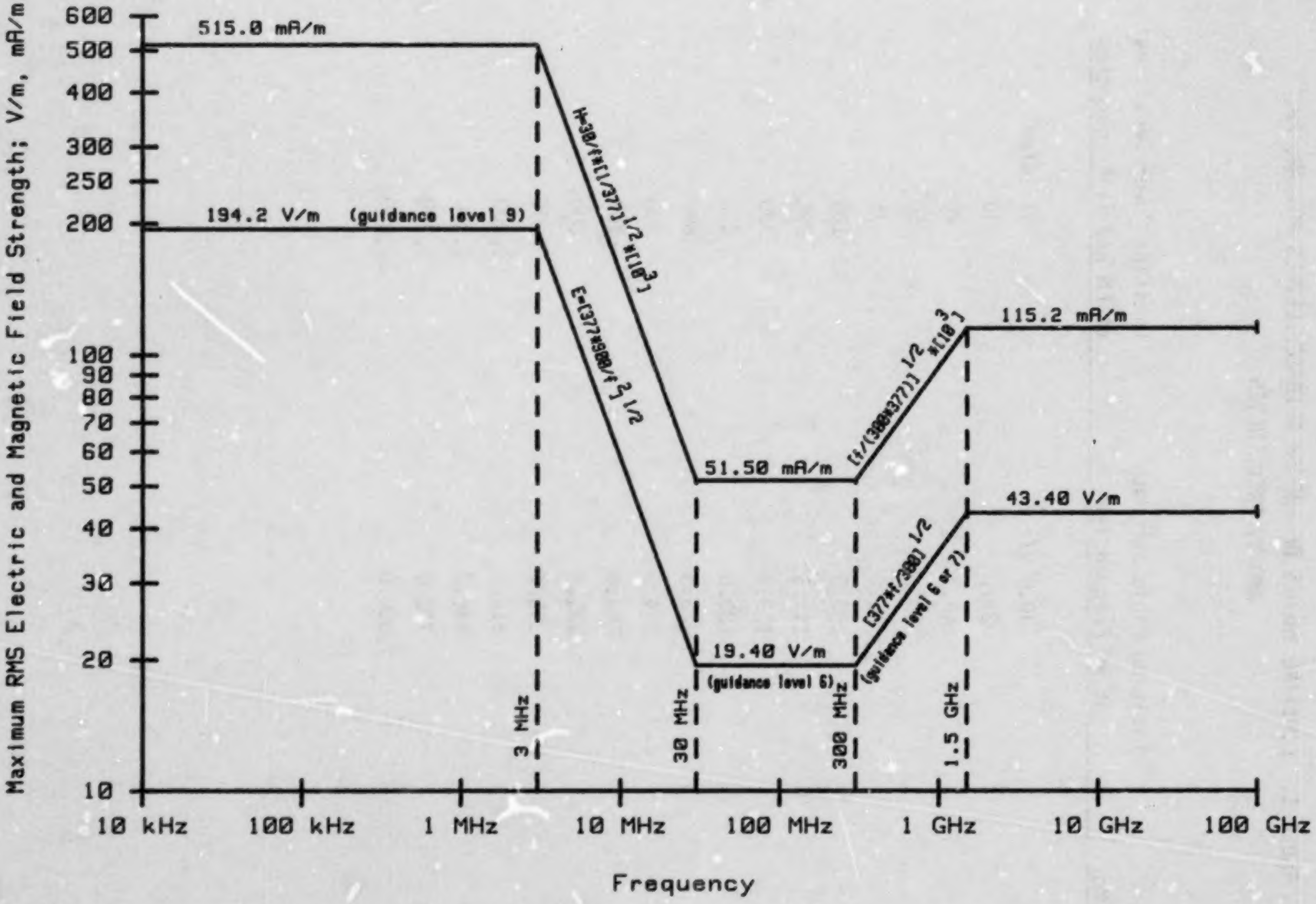

FIGURE 2. Hypothetical guidance shape to show application of impact results

levels examined in this report should allow combinations which may be used to determine the impact for any variations with frequency in the limiting exposure values which are finally proposed.

4. Impact on FM Stations

The impact of proposed EPA Federal guidance on the FM service was determined by application of a computer propagation model to most of the FM stations in the U.S. The computer model was developed by EPA using a combination of theoretical approximations and measured data. The large number of FM stations precluded the possibility of either onsite measurement or very detailed theoretical predictions for each source, so the model was designed to estimate the maximum, practically expected field strengths in order to compensate for the variety of conditions that may exist near an FM broadcast antenna. This means that the model may over-estimate the field strength in particular locations and thus represents a conservative approach to dealing with potential impact.

Typical FM broadcast antennas consist of one to sixteen elements (see Figure 3) in a vertically stacked broadside array. The elements are fed in phase and are spaced approximately one wavelength apart. Individual elements vary in shape and radiation pattern according to model and manufacturer. The ideal is an antenna that is omnidirectional in the azimuth plane (toward the horizon) and has a cosine or cosine squared pattern in any elevation plane. Elements are usually side mounted on a metallic tower but may also be center mounted on top of a tower. Figure 4 shows the distibution of tower heights for ground mounted FM towers in the EPA data base.

The energy in the antenna's main beam is specified in terms of effective radiated power (ERP). This value is the amount of power which must be radiated from a single dipole antenna in order to produce field strengths equivalent to those produced by the station at the same distance in the main beam. ERP's for FM stations generally range from a fraction of a kilowatt (kW) up to 100 kW. A station licensed for 100 kW of ERP will generally have 100 kW of horizontally polarized signal and 100 kW of vertically polarized signal as permitted by the FCC [3].

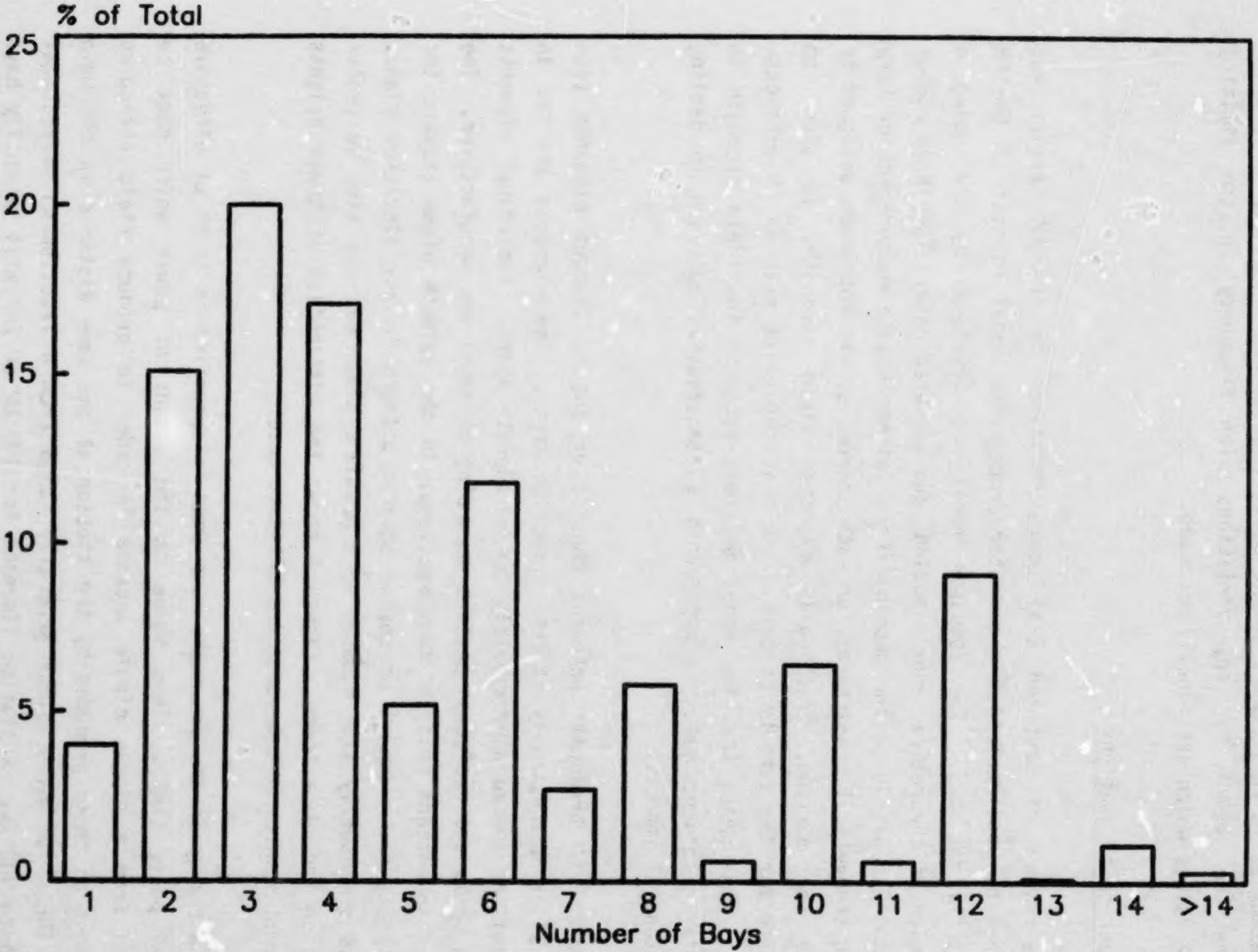

Figure 3. Distribution of numbers of elements in antennas for stations in the FM data base.

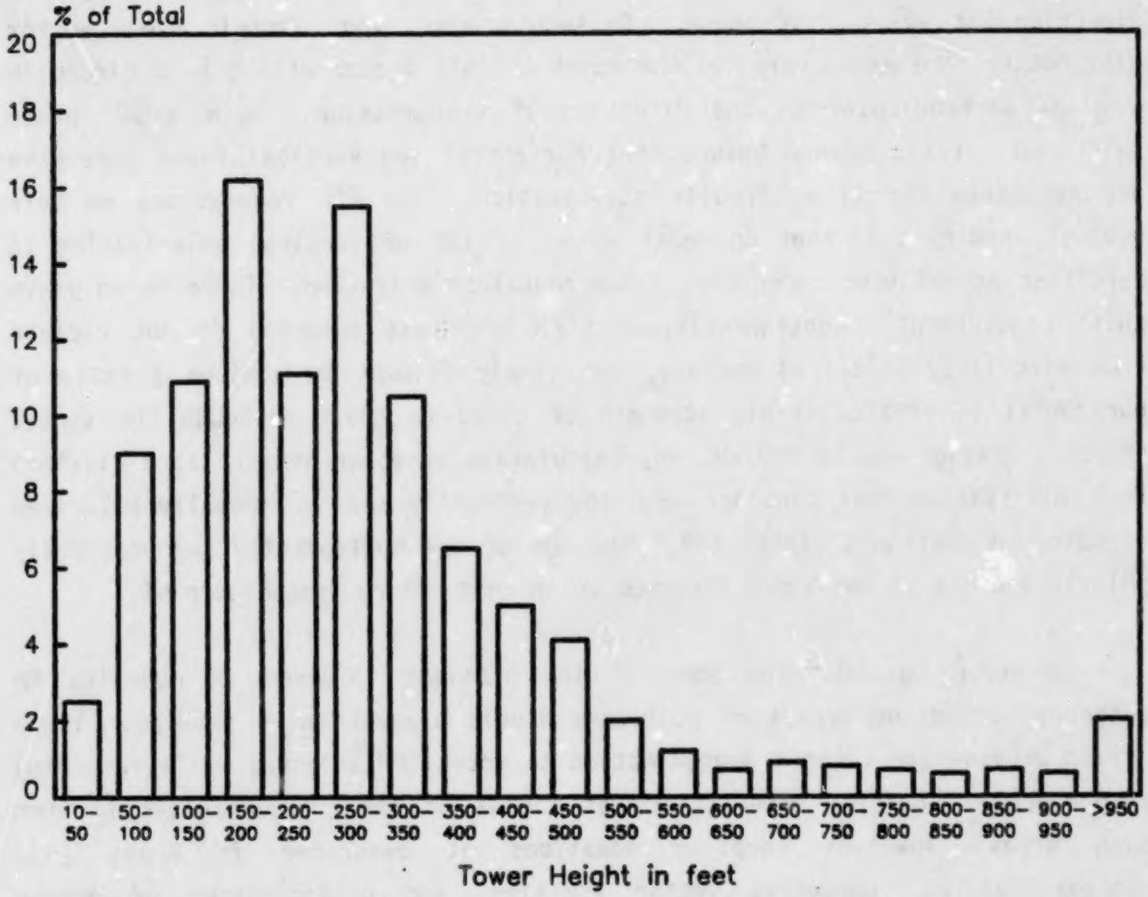

Figure 4. Distribution of tower heights for single ground-based FM stations in the FM data base.

There is some confusion over this point because the expression "circular polarization" is used in the FCC regulations [3] regarding this subject. True circular polarization is best described as a horizontally polarized signal and a vertically polarized signal of equal magnitude, traveling in the same direction but 90° out of phase. In such a case, the electric field vector will rotate once each cycle and the point of this vector will draw a circle in a plane perpendicular to the direction of transmission. Both a 90° phase shift and a ratio of one between the horizontal and vertical field strengths are necessary for true circular polarization. The FCC regulations on this subject specify only that an equal amount of ERP of vertical polarization is permitted as has been licensed for horizontal polarization. There is no phase shift requirement. Consequently, most FM broadcast antennas do not radiate true circularly polarized signals, but simply attempt to achieve a ratio of horizontal to vertical field strength of close to one. Although the stated ERP of a station may be 100 kW, any calculation of power density at a distance from the station must consider both the vertically and horizontally polarized signals. A station's "Total ERP," the sum of the horizontally and vertically polarized ERP's is sometimes referred to in this report (see Figure 5).

In order to determine some of the problems involved in modeling FM antennas, broadside arrays of half-wave dipole elements were studied. These arrays provide the closest approximation to actual FM antennas while remaining theoretically tenable. Predictions of fields on the ground resulting from such arrays involves coupling equations as described in Kraus [4], non-parallel ray geometry, vector addition, and consideration of ground reflections.

Coupling between broadside half-wave dipoles depends on the distance between elements and affects the impedance of the elements involved. For a given transmitted power, changes in impedance will affect the current flowing in each element and consequently the field produced by the element. Coupling effects were found to be small at one wavelength spacing between elements but very pronounced at half-wavelength spacing. Since most FM broadcast antennas use approximately one wavelength inter-bay spacing, coupling effects can be ignored in the design of an approximate propagation model (see Appendix A).

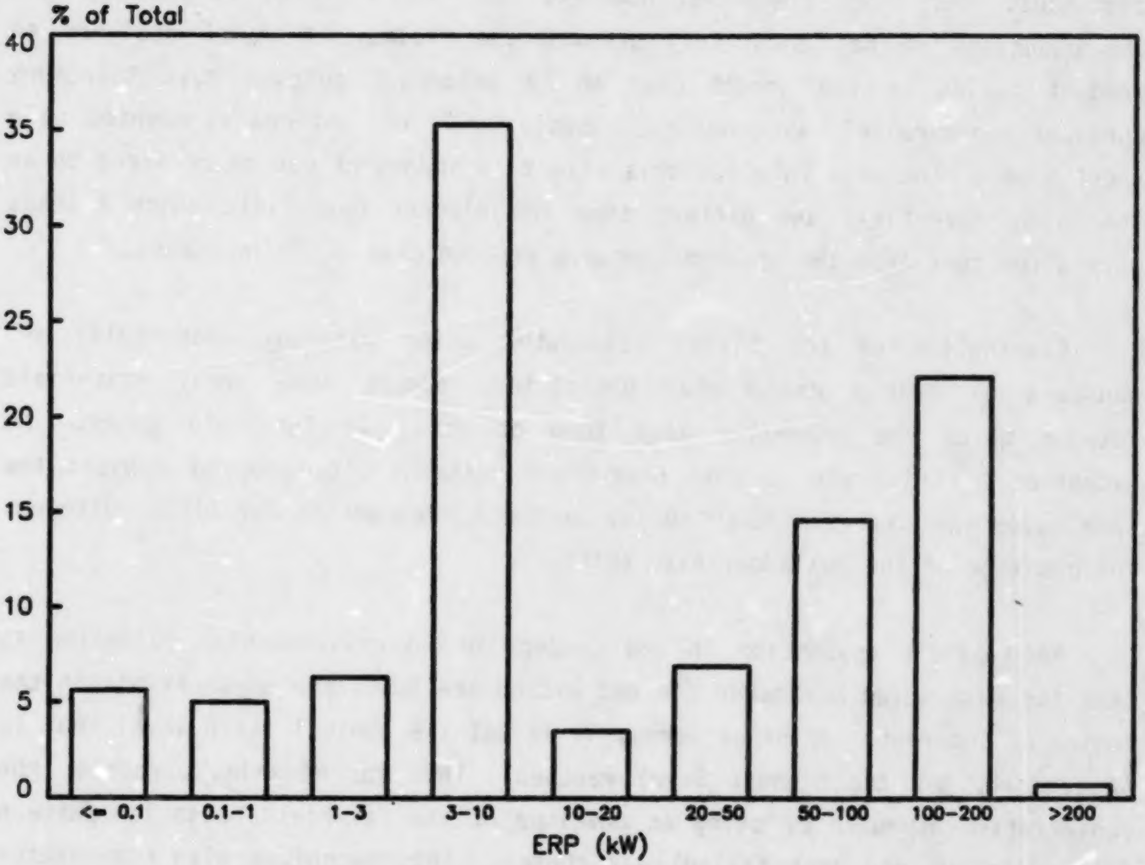

Figure 5. Distribution of total ERP's (horizontal and vertical) for stations in the FM data base.

Proper addition of the component fields from each element in the array requires knowledge of both the phase and magnitude of each signal. Simple equations have been derived for this addition at distances far from the antenna. These equations require that the rays from each element be practically parallel at the measurement point as is the case at far distances. For short distances, however, the rays will not be parallel and the equations do not accurately predict the fields. A model designed to predict fields on the ground near an FM broadcast antenna must therefore consider non-parallel ray geometry, especially if the antenna is mounted on a short tower. The area in which this effect is important can be referred to as the array near-field and differs from the element near-field which extends only a few feet from the antenna elements (in the case of FM antennas).

Examination of the fields calculated using parallel (far-field) and non-parallel (array near-field) geometries reveals that array near-field antenna gains are generally less than or equal to far-field gains. An exception to this rule is that near-field patterns often do not exhibit the same nulls (or have shallower nulls) as the corresponding far-field patterns. The position of the nulls may also shift.

An implicit assumption in the concept of an environmental guideline is that the restricted parameter can not exceed the guideline anywhere within the region of interest. In other words, it is not the typical field level that is of concern, but the highest level reached. Thus for modeling purposes, the conservative approach of using an envelope of the far-field radiation pattern (all nulls 100 per cent filled) was chosen. This technique also compensates for deliberate null-fill by some stations. The details of this technique are described in Appendix A.

A single normal reflection from a perfectly conducting plane surface will double the electric field strength at certain locations in space. While electric field strength (E) and power density (S) are not easily related under these conditions, a free space conversion ($S = E^2/377$) can be used for modeling purposes since the guidance is stated in terms of the maximum E, H, or S at FM frequencies. Thus the reflection described above could quadruple the free space equivalent power density at a given location. Larger increases in field are possible if multiple reflections are considered. Under realistic conditions, however, the ground beneath an FM broadcast antenna has a finite conductivity and dielectric constant. Equations such as those found in Jordan and Balmain [5] can be used to calculate the phase and reflection coefficient for waves reflected from finite conductivity ground. Examination of these equations over the typical ground conductivities and dielectric constants found in the United States and over the frequency range of FM stations shows that the magnitude of the voltage reflection coefficient averages less than 0.6 under the tower. In general, the resultant field will be less than 1.6 times the incident field since the magnitude of the reflection coefficient varies with angle of incidence, polarization, and the ground constants. However, 1.6 was chosen as a constant multiplying factor to be used in the model to cover the variable height above ground of the measurement point (the guidance may limit fields at any height above ground that are easily accessible), the unknown angles of nearby terrain, and the possibility of more reflective materials in the vicinity. This multiplying factor is not valid at far distances, but the primary area of concern for this analysis is within a few hundred feet of the tower (see Appendix A).

FM antenna manufacturers do not typically provide measured elevation patterns for their elements. The data they do provide gives information about the main beam characteristics of their antennas and is not useful in predicting the fields on the ground near the tower. In order to determine this information, EPA obtained via a contract [6] measured elevation radiation patterns of five commonly used FM broadcast elements. Elevation patterns of each element were measured at four different azimuth angles with the elements mounted on a dielectric support and then repeated with the elements leg mounted and face mounted on a metallic tower section. The final report for EPA contract number 68-03-3054 [6] contains the results of these measurements along with an explanation of the measurement technique. The twelve elevation patterns were overlaid and an envelope drawn around the extremes of the patterns to produce a single worst-case elevation pattern for each polarization of each element. This worst-case envelope was used to represent the element in the propagation model. This approach helps insure that the model will not underestimate the fields in any direction away from the tower or for any common antenna mounting method. The resulting envelope was then digitized at five degree intervals for use in the model (see Appendix A for more details).

Stations in EPA's FM data base were examined to determine how many stations actually used the five element types characterized for this study. The results are shown in Table 2 which indicates that the measured elements represent approximately 46 percent of the elements in use at the time the data base was assembled. Another 25 percent were of the ring-stub or cycloid design. While elevation patterns for this type of antenna were not measured under the contract, limited measurement data obtained from one manufacturer indicates that it has an element pattern similar to element type 1, which was measured under the contract. The remaining approximately 28 percent of the elements which did not fall into any measured category along with all ring-stub antennas were modeled as type 1 elements since these produce the highest field levels on the ground of any measured. This decision was based on the desire to overestimate rather than underestimate impact when substantial approximations are used.

TABLE 2. DISTRIBUTION OF ELEMENT TYPES IN THE EPA FM DATA BASE

Element Type	Number in Data Base	Percent of Data Base
Type 1	563	14.41
Type 2	397	10.16
Type 3	350	8.96
Type 4	314	8.03
Type 5	188	4.81
Ring-Stub	989	25.3
Other	1,107	28.33

Mitigation Strategies

Modified versions of the FM model were developed in order to examine possible mitigation strategies. The model in its original form can determine the number of stations likely to exceed a given guidance level, but only with a knowledge of the corrective measures that might be chosen and the effectiveness of these measures can impact costs be assigned. EPA explored several approaches to this problem and discussed these ideas with industry consultants and antenna manufacturers. The result was a sequence of corrective measures or "fixes" that would most likely be chosen by a station in non-compliance (Figure 6). The sequence is ordered by increasing cost and it is assumed that a station would choose the least expensive measure that is effective in bringing their facility into compliance.

Examination of measured antenna elevation patterns reveals that some antennas direct much less energy towards the ground than others. In many cases, a simple change to one of these "better" antennas is all that is needed to bring a station into compliance. This approach is the least expensive "fix" and is therefore first in the sequence of corrective measures. The FM model can check the effectiveness of this approach by simply replacing a station's antenna with a "better" one if it is not using one at present.

Since the pattern of an FM antenna is a combination of the element pattern and the array pattern, another approach to mitigation is to reduce downward radiation in the array pattern. At one wavelength element spacing, the spacing typically used for FM antennas, the array pattern shows downward radiation equal to that in the main beam. This effect occurs because the wave from each element adds in phase with all other elements in the array in the downward direction. If the spacing is reduced to one-half wavelength (for an even number of bays antenna), each wave has an out-of-phase counterpart and downward radiation is eliminated. Fields on the ground will still occur at angles slightly different than directly downward, but will be greatly reduced. The drawback of using this method is that the increased coupling that occurs at one-half wavelength reduces the gain of the antenna. In order to maintain the original gain of the antenna, the number of bays must be approximately doubled. Another way to reduce downward radiation is to reduce the interbay spacing such that waves from element (n) and element (N/2 + n) are exactly out of phase, where n indexes the elements in an N bay array. Thus, the required interbay spacing would vary as shown in Table 3:

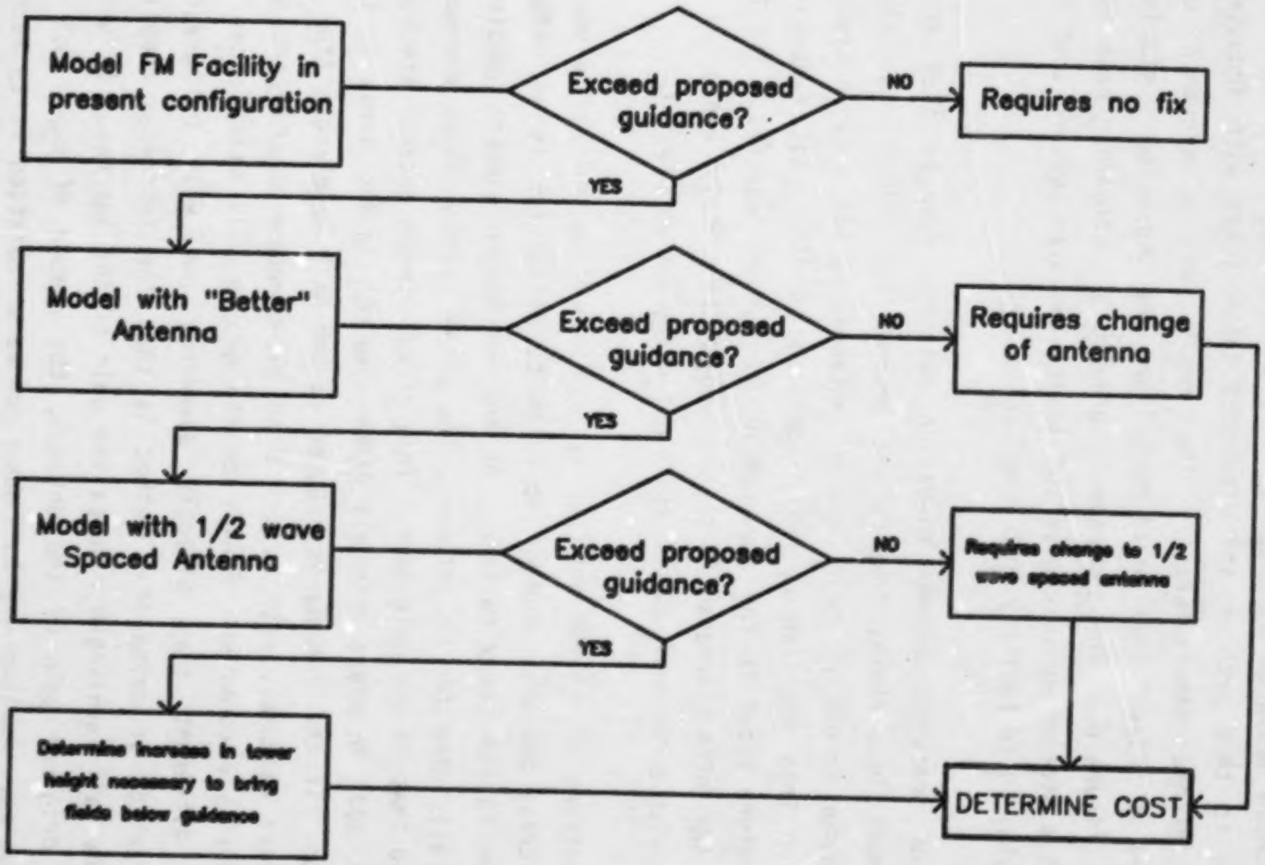
Model FM Facility in present configuration
Exceed proposed guidance?
NO
Requires no fix
YES
Model with "Better" Antenna
Exceed proposed guidance?
NO
Requires change of antenna
YES
Model with 1/2 wave Spaced Antenna
Exceed proposed guidance?
NO
Requires change to 1/2 wave spaced antenna
YES
Determine increase in tower height necessary to bring fields below guidance
DETERMINE COST

Figure 6. Determination of compliance costs for FM stations.

TABLE 3. INTERBAY SPACINGS TO REDUCE DOWNWARD RADIATION IN THE ARRAY PATTERN

Number of bays	Interbay spacing in wavelength units
2	0.50
4	0.75
6	0.83
8	0.88
10	0.90
12	0.92
16	0.94

A smaller increase in number of bays would be required to maintain the same gain for this method than for one-half wave spacing, but feeding the array would be more difficult since the length of transmission line between bays determines phasing. For one-half wave spacing, criss-crossing the transmission line or turning alternate elements upside down yields proper phasing. Antenna manufacturers would probably achieve decreased downward radiation in a variety of ways depending on the characteristics of their particular elements.

Altered inter-bay spacing was chosen as the second probable mitigation method since the cost is higher than replacement with an already existing "better" antenna. Exact modeling of this fix is difficult because the optimum spacing may differ for various antennas. Coupling effects at less than one wavelength spacing are prominent and not easily calculated by theoretical means. EPA has explored this problem through use of the Lawrence Livermore National Laboratory (LLNL) numerical electromagnetic code (NEC) [7] to calculate coupling effects and the resulting patterns [8]. The results of this study indicate that an increase in the number of bays would be necessary to maintain the same gain. Figures 7, 8, and 9 show the effects of altered spacing for three commercially available FM antenna elements. As an approximate solution, EPA modeled this fix as the combination of measured element patterns and the far-field array patterns for one-half wavelength spaced isotropic elements. The array patterns were for an increased number of bays to replace the original array in order to compensate for the loss in

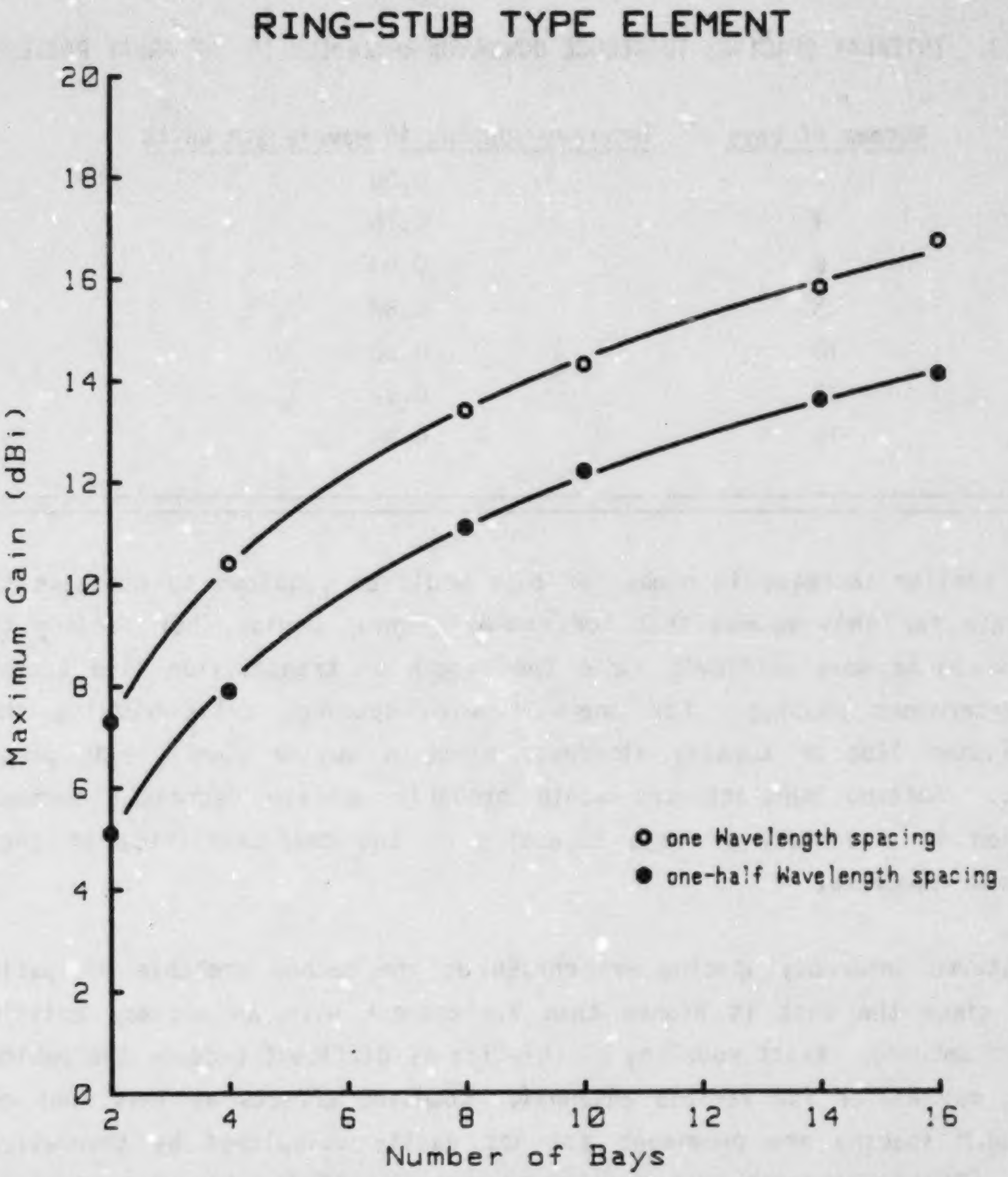

Figure 7. Antenna gain as a function of number of elements for one-half and one wavelength spacing between ring-stub type elements.

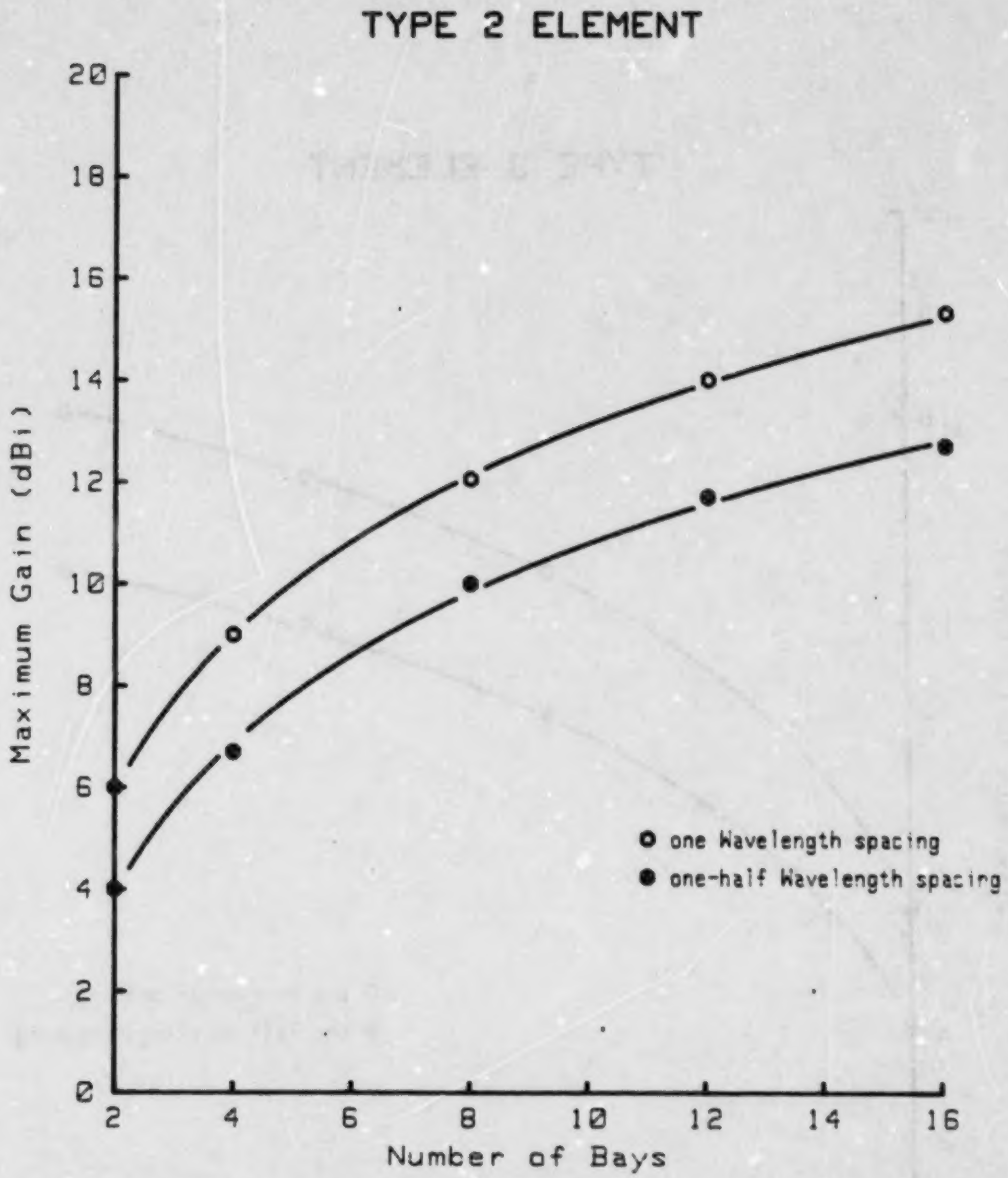

Figure 8. Antenna gain as a function of number of elements for one-half and one wavelength spacing between type 2 elements.

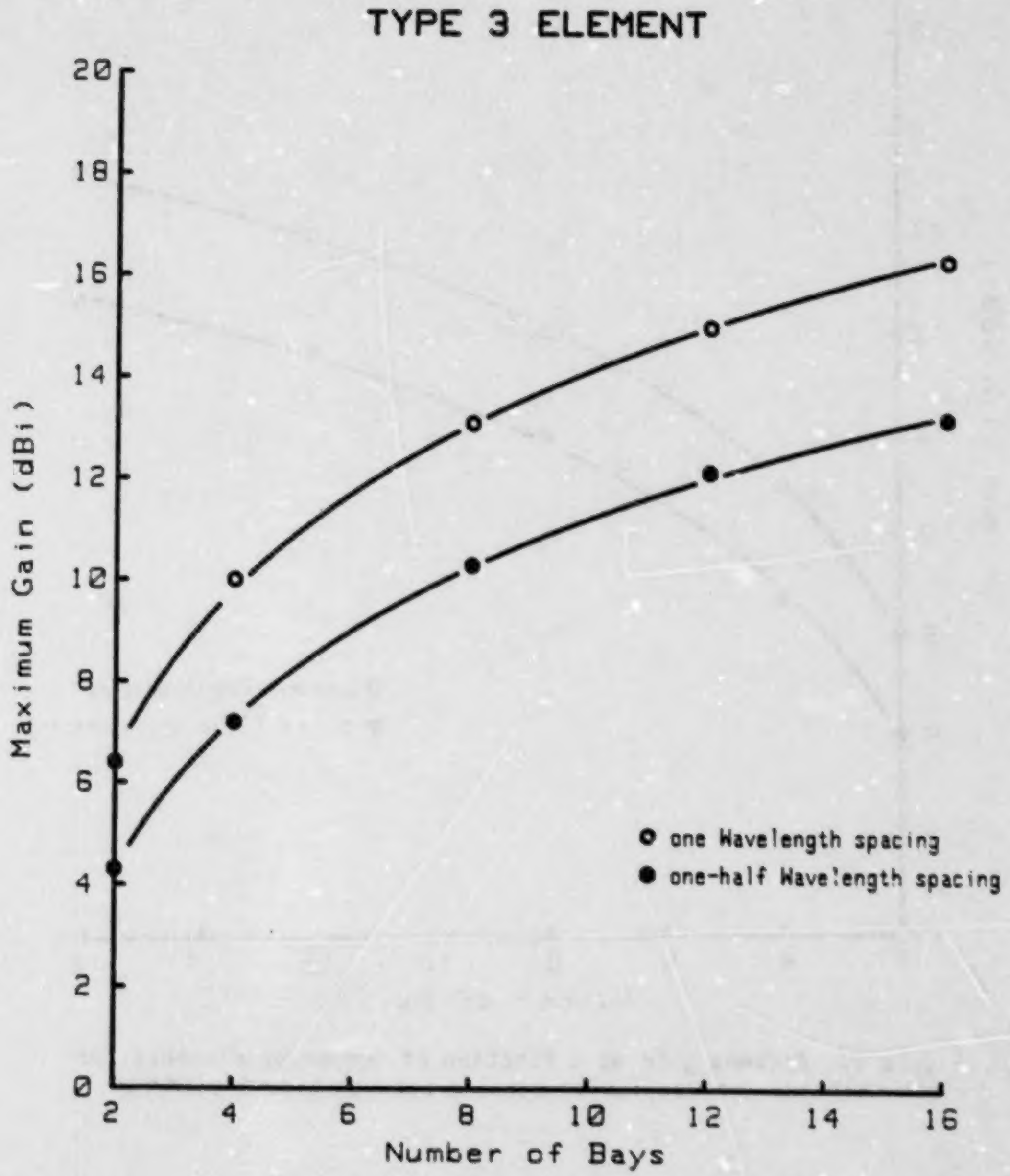

Figure 9. Antenna gain as a function of number of elements for one-half and one wavelength spacing between type 3 elements.

gain at closer spacings. Table 4 shows the increases used for various sizes of antenna arrays. This approach tends to overestimate impact since the greater than half-wave spacings shown in Table 3 might be used and would require a smaller increase in number of bays.

TABLE 4. NUMBERS OF BAYS USED IN ONE-HALF WAVELENGTH MODEL

Actual number of bays in array	Number of bays used in 1/2 λ model to approximate same gain
1	2
2	4
3	6
4	8
5	8
6	10
7	12
8	14
10	16
12	18
14	20
16	24

Stations which were not in compliance at any given guidance level either in their present configuration or with an antenna change were then modeled with one-half wavelength spacing. This "fix" proved to be very effective in bringing stations into compliance.

The third mitigation measure examined involved raising the tower height until field levels on the ground fell below the guidance level. Since increasing tower height is expensive, it was assumed that stations requiring a height increase would also use altered interbay spacing to minimize the amount of tower height increase necessary. In some cases, tower height increases may not be possible because of FCC regulations limiting maximum height above average terrain (HAAT) or because of land limitations (for guy wires). However, broadcast consultants have indicated that this fix is a reasonable third choice in situations where the first two approaches are not sufficient.

Operation of the FM Propagation Model

The following data for an FM broadcast station are required to apply the propagation model:

Horizontal ERP (Effective Radiated Power)
Vertical ERP
Antenna model and make
Height above ground to center of radiation of the antenna
Number of bays in the antenna

Beginning at one meter from the base of the tower, and proceeding at two meter intervals, the model calculates the elevation angle of each point with respect to the antenna center of radiation (Figure 10). Relative field strength values from the element pattern (Figure 11) and array pattern (Figure 12) are then found at this angle by interpolation.

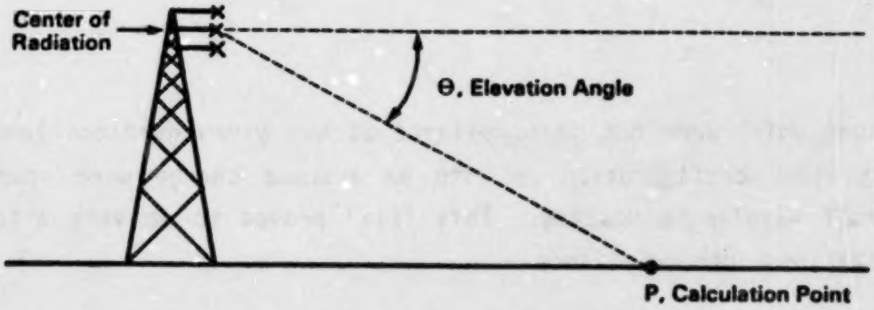

Figure 10. Elevation angle to a field calculation point.

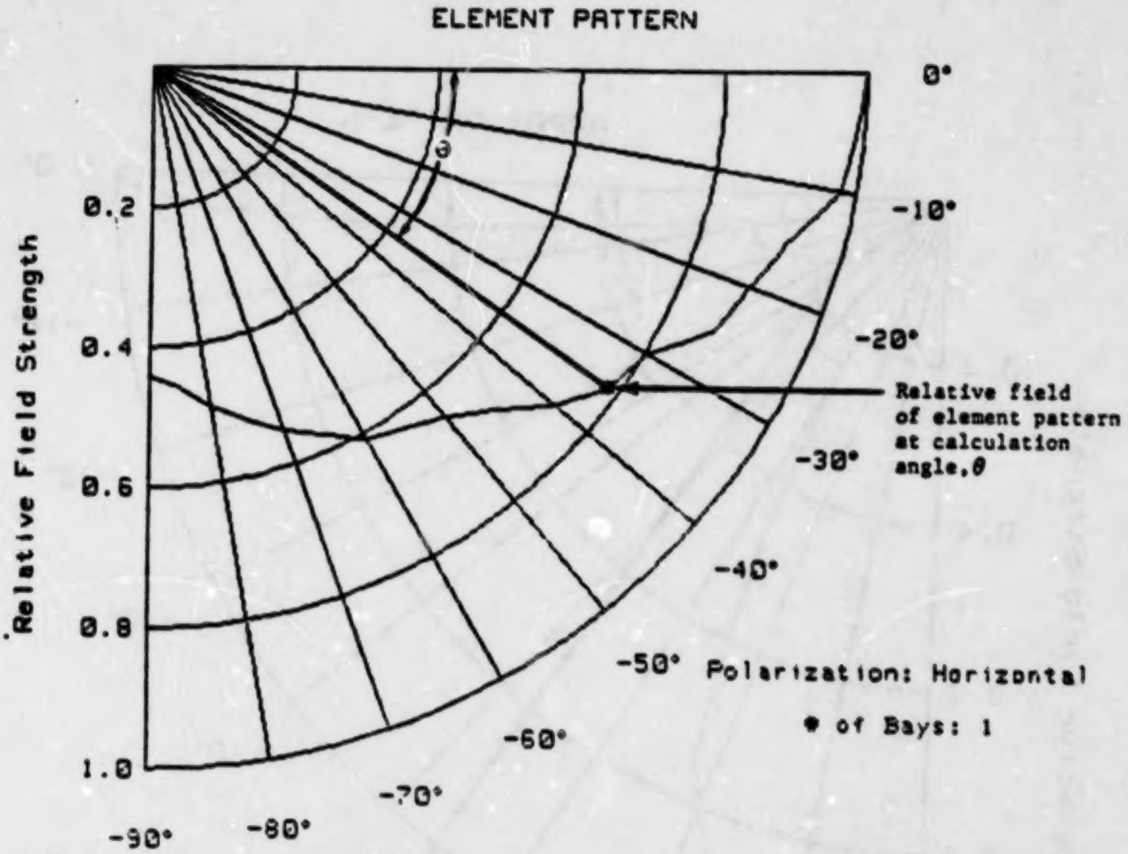

Figure 11. Relative field strength pattern of a single element.

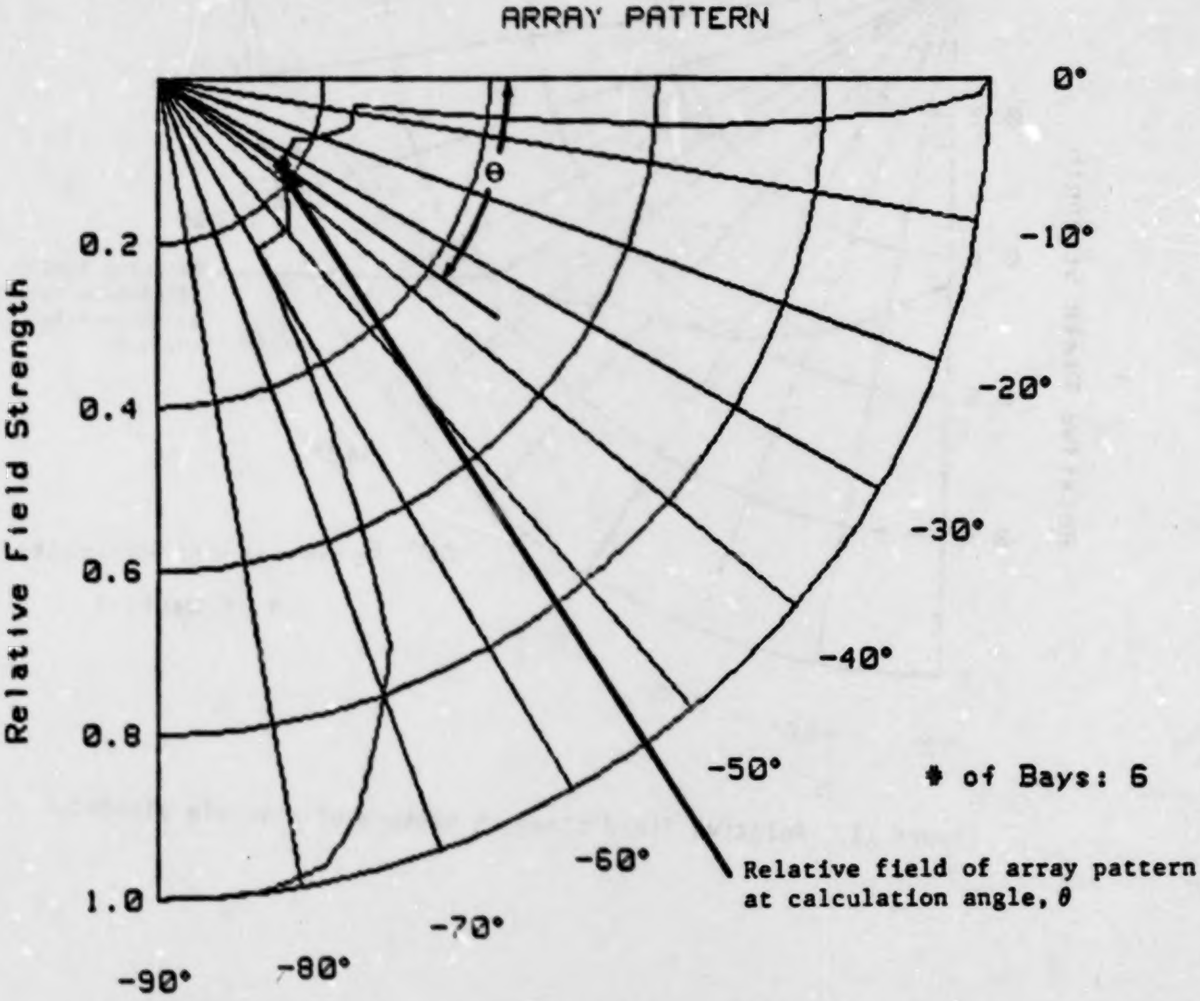

Figure 12. Relative field strength array pattern for a 6 bay array.

The two values are multiplied to give the total relative field for the direction to that point. This total is squared to yield the relative power and multiplied by the ERP to provide an "adjusted ERP" corresponding to this direction from the antenna.[1] The equation

$$S\ (\mu W/cm^2) = \frac{\text{(Adjusted ERP in watts)} * 1.64 * 2.56 * 100}{4 * \pi * (\text{Distance})^2}\ \mu W/cm^2 \qquad (1)$$

is then used to calculate the power density at the point. The factor of 1.64 corrects for the fact that ERP's as defined by the FCC are relative to a one-half wave dipole element. The factor of 2.56 is the square of the reflection factor, 1.6, discussed earlier for realistic ground conditions. The "distance" in the equation is the distance in meters from the center of radiation to the calculation point.

As the power density is calculated at each point, it is compared to a set of eighteen alternative guidance levels. These are 1, 10, 20, 50, 75, 100, 200, 300, 400, 500, 600, 700, 800, 900, 1,000, 2,000, 5,000, and 10,000 microwatts per square centimeter ($\mu W/cm^2$). If the calculated power density exceeds any of these alternative guidance levels, the distance from the base of the tower to the calculation point is stored in the corresponding element of an eighteen element mathematical array. This process is repeated as the model steps away from the tower so that the final numbers stored in the array are the farthest distances away from the tower at which the eighteen guidance levels are exceeded. The highest power density reached at any point along with the distance at which it occurs is also stored. This peak power density or S_{peak} typically does not occur directly underneath the antenna. A sample output from the model is shown in Figure 13.

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[1] This "adjusted ERP" differs from the ERP specified by the FCC which refers to the power in the main beam.

```
Antenna:    TYPE 2                              6  Bays
Tower Height:   10.668 m
Total ERP (H+V):   200 kW

Distance from                  Power
Tower (Meters)                 Density (µW/cm²)

        2497                         1
         802                        10
         558                        20
         345                        50
         261                        75
         220                       100
          39                       200
          25                       300
          16                       400
          13                       500
          13                       600
          10                       700
          10                       800
           5                       900
           5                      1000
           5                      2000
           3                      5000

PEAK POWER DENSITY = 6185.32 uW/cm2 AT 3.20 METERS FROM TOWER BASE
PEAK FIELD STRENGTH = 152.70 V/M
```

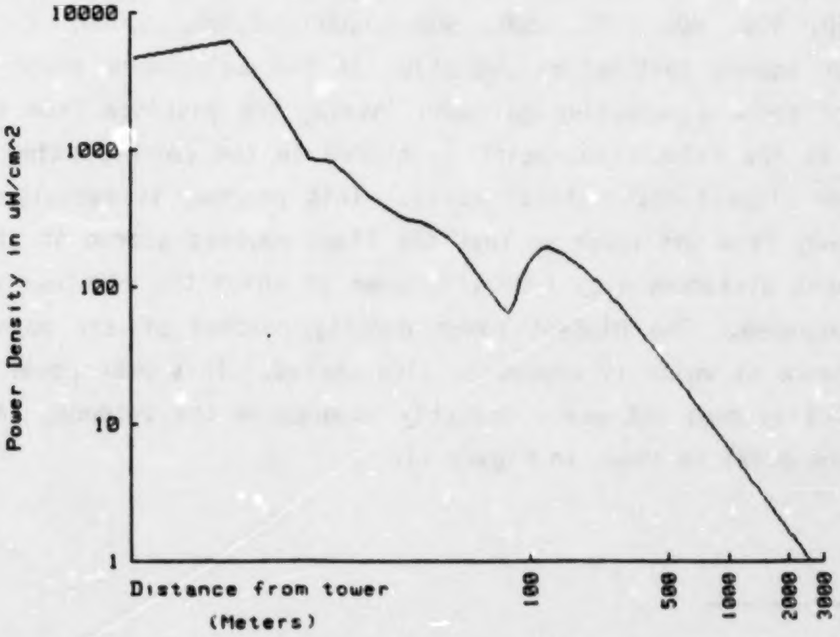

Figure 13. Power density near the ground as a function of distance from a 6-bay FM array with the lowest element 10.7 m above ground.

The model output was designed to facilitate a more detailed impact analysis using information on land ownership and fencing. It was intended that this information be obtained through surveys for comparison with the distances to each guidance level predicted by the model. If a station was already fenced to a distance of ten meters from the tower, only those power densities predicted to occur outside the fenced areas would be considered for impact. Similarly, if the station owned property around the tower which was not fenced, fencing would be considered as an alternative mitigation strategy. The survey results would also indicate how many stations are located in remote areas so that posting radiation hazard signs might serve as an adequate "fix".

A statistically based questionnaire survey of FM radio stations was accomplished in early 1984 after most of this impact analysis had been completed. Preliminary results are shown in Appendix F. As a rough indication of the possibility of posting, a computer automated population data base of the 1980 United States census [9] was employed to examine population densities around a sample of 878 FM broadcast antennas having predicted ground level fields in excess of 100 $\mu W/cm^2$. Using the coordinates of these transmitters from the FCC data base, the 1980 population data base was examined to see how many of the station locations showed zero population in circles of 0.5, 1, 2, 3, 4, and 5 km radius centered on the towers. The results (Table 5) actually represent whether or not a census enumeration district (CED) occurs within the radius, since the data base is structured only by CED's. However, the density of CED's is directly related to the population density and provides a reasonable indication of the remoteness of the station.

TABLE 5. NUMBER OF FM RADIO STATIONS (FROM A SAMPLE OF 878) HAVING NO CED's WITHIN 0.5 to 5.0 km

Radius (km)	Number of stations with no CED's
0.5	713
1.0	529
2.0	325
3.0	196
4.0	122
5.0	83

In order to obtain better coverage, many FM transmitters are located on remote mountain tops. Many of these mountain top stations have short towers and produce relatively high field strengths on the ground near the tower. It is likely that these stations comprise a large percentage of those predicted to be impacted by various proposed alternative guidance exposure levels. If so, actual impact would be significantly less than predicted here since posting and fencing are generally less expensive than the other "fixes" used in the model. Thus, until such time as a detailed survey of land use in the vicinity of FM towers is completed, it must be emphasized that the impact estimates reported here should be interpreted as upper limits; in reality, actual impact should be less and may be significantly less.

The increase in tower height "fix" was calculated using a variation of equation (1) along with a distance factor. First, the total pattern for the station is found by multiplying the station's element and array patterns. The total pattern shown in Figure 14, for example, is the product of the element and array patterns shown in Figures 11 and 12. Next, the total pattern is multiplied by (sin θ) to correct for the variation in distance which the radiation must travel as a function of angle before reaching the ground (see Figure 15).

The total pattern multiplied by the distance factor (sin θ) is shown in Figure 16. The angle at which maximum field strengths will occur on the ground (θ_m) is equal to the angle at which a maximum occurs in this pattern regardless of tower height. Once an "adjusted ERP" is found for this angle, the minimum tower height necessary to bring the station into compliance can be found using equation 2.

$$\text{MTH} = \sqrt{\frac{(\text{Adjusted ERP in watts}) * 1.64 * 2.56 * 100 * \sin^2(\theta_m)}{4 * \pi * (\text{guidance level } \mu\text{W/cm}^2)}} \qquad (2)$$

MTH = minimum tower height necessary to bring station into compliance in meters

θ_m = angle at which maximum radiation reaches the ground

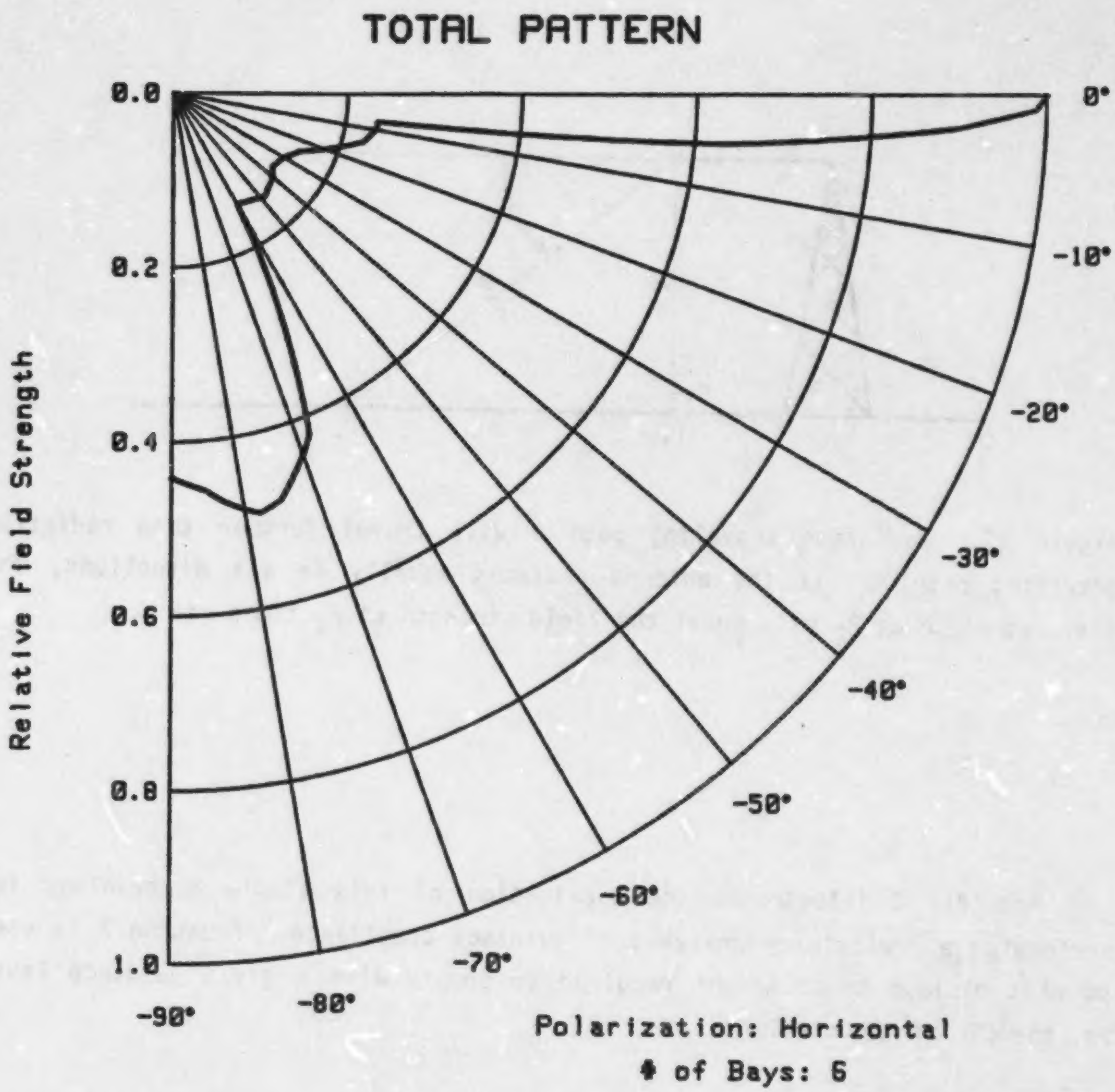

Figure 14. Total pattern of a 6 bay array; this is the product of the element pattern (Figure 11) and the array pattern (Figure 12).

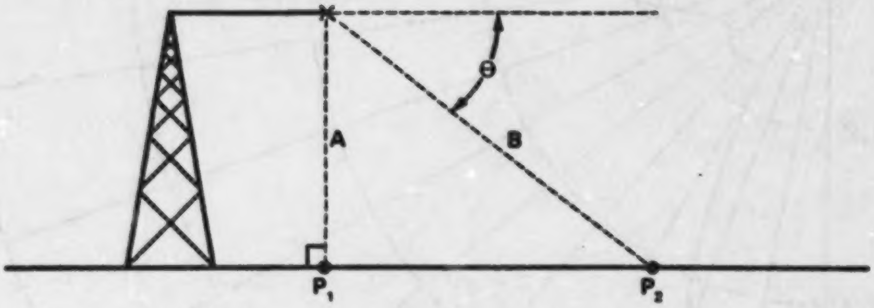

Figure 15. Radiation traveling path B will travel further than radiation traveling path A. If the antenna radiates equally in all directions, the field strength at P_2 will equal the field strength at P_1 times sin θ.

Appendix C illustrates the application of this simple methodology for performing a preliminary analysis of guidance compliance. Equation 2 is used to plot minimum tower height required to comply with a given guidance level vs. the ERP of the station.

Multiple Sites

In many cases, more than one FM station locates its broadcast antenna on the same tower. The FCC automated data base does not indicate which stations are co-located, but it does contain the longitude and latitude coordinates of each station's tower. By computer searching for matched coordinates, EPA was able to determine which stations were co-located. This technique does not distinguish between antennas which are on the same tower and towers that are separated by less than about 100 feet due to the resolution of the coordinates as recorded on FCC forms by each station, but for modeling purposes, matched

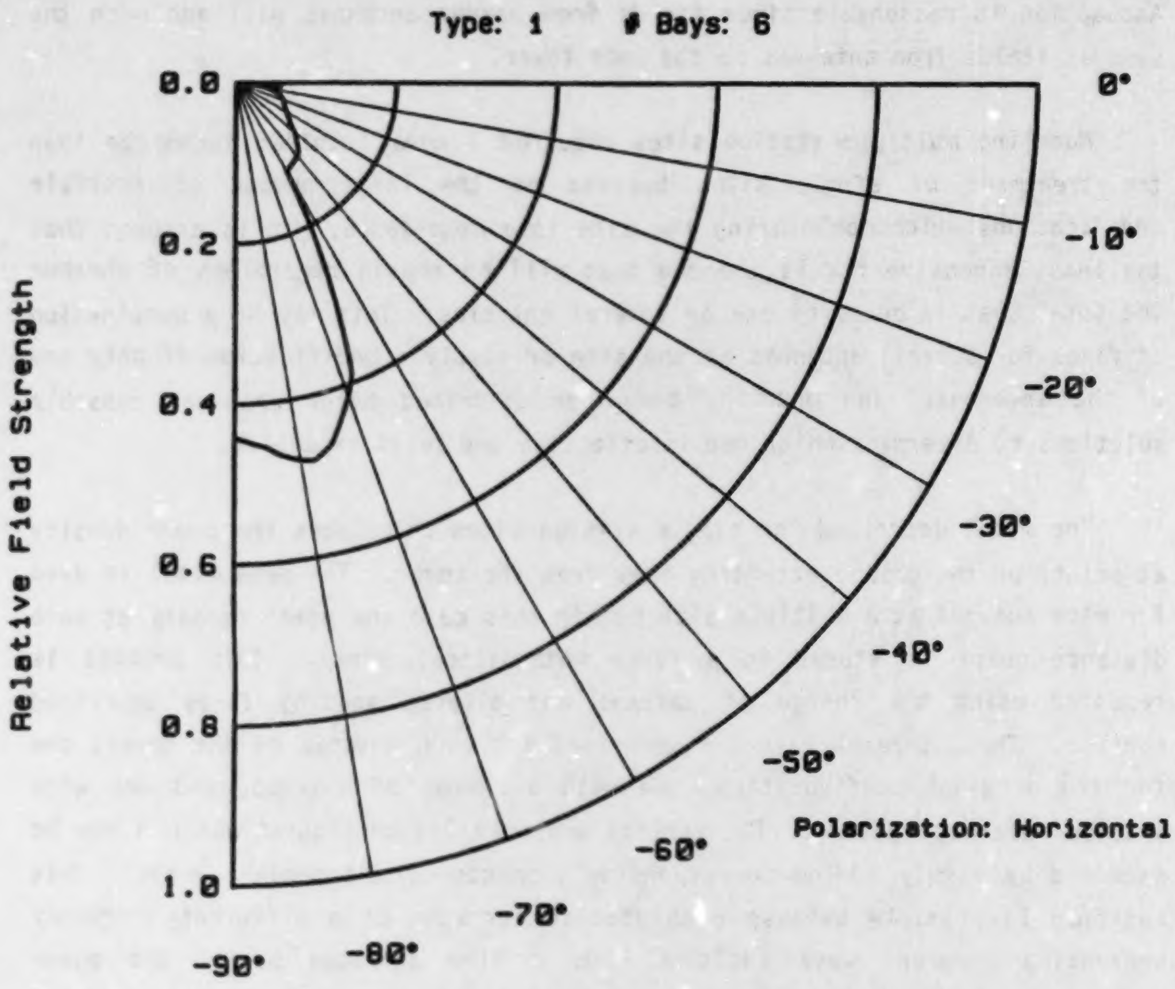

Figure 16. Total array pattern multiplied by the distance factor (sin θ).

coordinates were assumed to indicate antennas on the same tower. This assumption is reasonable since fields from nearby antennas will add much the same as fields from antennas on the same tower.

Modeling multiple station sites required a more involved technique than the treatment of single sites because of the large number of possible modifications which could bring the site into compliance. It is assumed that the least expensive fix is the one that will be chosen regardless of whether the total cost is borne by one or several entities. This may be a combination of fixes for several antennas at the site or simply a modification of only one of the antennas. The modeling technique described below examines possible solutions to determine which one is effective and least expensive.

The model described for single station sites calculates the power density at points on the ground extending away from the tower. The same model is used for each antenna at a multiple site but in this case the power density at each distance point is stored in a large mathematical array. This process is repeated using the change of antenna and altered spacing fixes described earlier. Thus, three arrays are generated for each antenna on the tower, one for the original configuration, one with a change of antenna, and one with altered interbay spacing. The various possible fix configurations can now be examined by simply adding corresponding elements of the proper arrays. This addition is possible because each station operates at a different frequency preventing coherent wave addition. On a time averaged basis, the power densities from each station can be added directly (Figure 17).

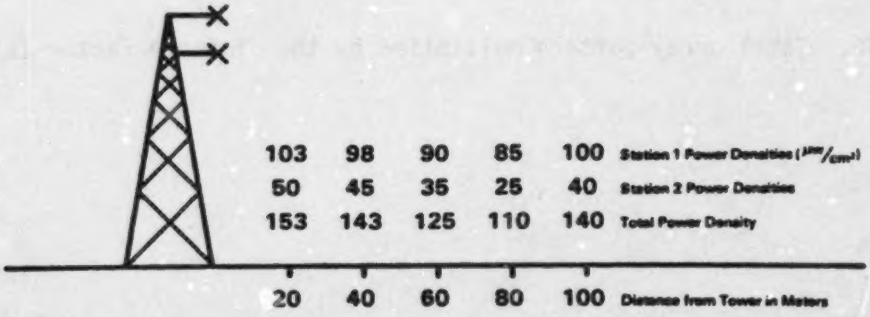
103 98 90 85 100 Station 1 Power Densities (µW/cm²)
50 45 35 25 40 Station 2 Power Densities
153 143 125 110 140 Total Power Density
20 40 60 80 100 Distance from Tower in Meters

Figure 17. Summation of power densities from two stations on the same tower.

The first step in analyzing a multiple site is to add the arrays for each station in its present antenna configuration. The resulting array is then checked to see if a given alternative guidance level is exceeded at any point. If not, the site is considered a non-problem at that guidance level. If the site does exceed the alternative guidance level, the distance points at which the alternative level is exceeded are identified. The power densities from each antenna are then examined at those points to determine which antennas are creating more than some specified fraction of the guidance level under consideration. For purposes of this analysis, this fraction (1/n) was arbitrarily defined to be the reciprocal of the number of stations (n) at the site. It is assumed that only those stations exceeding (1/n * 100) per cent of the guidance level would be required to make changes in their facilities. These stations are considered for changes to bring the site into compliance.

The next step is to subtract the power density array for the station (in the subset exceeding 1/n * 100 per cent) with the lowest number of antenna bays from the total power density array and replace it with that station's "change of antenna" array. The new total array consists of the power densities predicted to result if the above specified station changes to a new antenna and all others remain the same. This total array is then checked to see if it still exceeds the guidance level. If so, the next lowest number-of-bays station in the subset is changed to a new antenna and the total checked again. If the power densities still exceed the guidance after all the stations in the subset are changed to a new antenna, then the replacement process is repeated using altered interbay spaced antennas. Once the power density at the site falls below the guidance level, the changes made up to that point are recorded and the replacement process is ended. The output is a table for each alternative guidance level showing the numbers of stations requiring each kind of fix grouped by the number of bays in their antennas. The output format contains no information about the number of stations at each specific site requiring a fix, but does contain the total numbers of stations at all sites in the data base requiring each kind of a fix. The latter is easier to work with and is adequate for impact analysis costing.

Building Mounted Towers

Approximately ten per cent of all FM stations (licensed American, 1980 data) are located on top of buildings. Typically, they are mounted on a short tower which is secured to the building rooftop. In nearly all cases, the ground around the building is shielded from the downward beams or grating lobes by the building rooftop. The height of the building also reduces the intensity of any radiation reaching the ground (see Figure 18). Areas which must be considered in terms of guidance levels are the rooftop itself, the interiors of adjacent buildings, and the top floor of the building on which the tower is mounted.

High field levels are often found on rooftops supporting FM towers. The low towers and metal roofs frequently used for such buildings account for these levels. Aside from the field level hazard, there may also be a shock (RF burn) hazard when the bottom element is within reach. However, for the purposes of this study, it was assumed that very few such rooftops are accessible to the public. It is realized that in certain high-rise city environments, this assumption may be invalid.

Locations on the top floors of these buildings are not usually exposed to high levels of RF radiation because of the shielding provided by the rooftop building materials. A metal rooftop, while greatly increasing field intensities on the roof due to reflections, will effectively shield the interior of the building. Other materials are less effective, but the simple application of metal screen to the rooftop surface will eliminate any significant field levels in the unusual case that such are present.

Finally, an issue of some concern has been the creation of high field levels in adjacent buildings by exposure to an antenna's main beam through windows or walls. Such a situation occurs when new buildings constructed near a building mounted station are higher than the broadcast antenna or at least high enough to intercept the antenna's main beam. This presents a problem for the station as they have now lost part of their coverage by obstruction of their beam.

These situations were not treated in the impact analysis for several reasons. First, broadcast consultants indicated that these cases are usually self-correcting. In other words, the station chooses to move to a higher building in order to regain lost coverage. Such a move is not dictated by

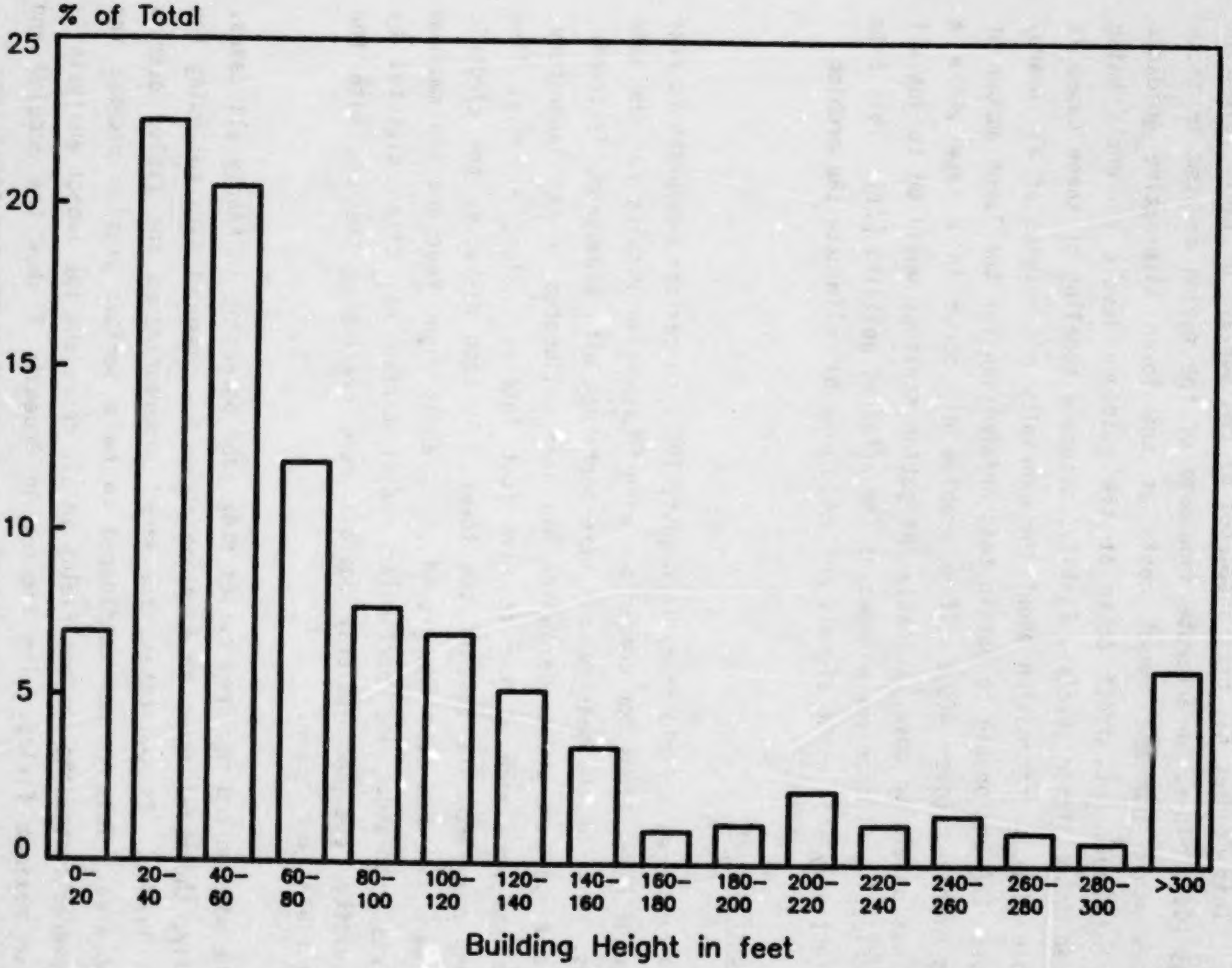

Figure 18. Distribution of Building Heights Supporting FM Towers.

Federal guidance and thus cannot be included as an impact. Second, the building materials can typically attenuate the fields by about 6 dB [10], reducing exposures below the levels currently being considered for the guidance. This concept has been supported by EPA surveys of field levels in buildings [11]. Thus, an accurate knowledge of the fields created in these situations would increase impact costs at the lower alternative guidance levels, but would not affect costs at the guidance levels currently being considered or at higher levels. Finally, accurate modeling of these cases is impossible without information about the proximity and heights of all nearby buildings. EPA was unable to obtain this information for the large number of stations involved (over 400). If a problem did occur in a case where a station was unable to move, a likely mitigation strategy would be to install solar reflective film on the windows of the affected building [11]. This film very effectively shields RF signals and would probably eliminate the problem.

Model Verification

EPA conducted a field study in August, 1982, to perform measurements near a sample of FM stations for comparison with FM modeling results for the same stations. Most of the measurements were performed with broadband, isotropic, electric field strength probes which had been calibrated in the laboratory. Measurements were made at two to five foot intervals along a radial line extending away from the base of the tower. At each distance, the electric fields were examined from the ground up to about eight feet and the maximum value was recorded. The particular radial chosen was often dictated by accessibility, but when several radials were available, the one with the highest fields was chosen.

The modeled and measured curves show good agreement in nearly all cases. Typically, the model draws an envelope above the measured data following the general trends. In two cases, the model underestimated the fields over a limited area. This is not considered to be a serious problem because the model overestimates the maximum fields in all cases and the impact analysis is based on maximum fields. The figures in Appendix B show the modeled and measured curves for each station plotted on the same graphs for comparison.

FM Modeling Results

The FM model was applied to approximately 3,300 FM stations with ground mounted towers for which EPA had complete data. Single FM stations with ground mounted towers (SFMG) accounted for 2,908 of the stations while the remaining 357 belonged to multiple FM broadcast locations with ground mounted towers (MFMG). The results are presented in Tables 6 through 23 for the 18 exposure levels studied. Table 11, for example, gives the number of SFMG stations (by number of bays) exceeding the given guidance level (column labeled # Stations > S) and the number requiring an antenna fix, or an altered interbay spacing fix, in order to comply with a 100 $\mu W/cm^2$ level. The "Antenna and 1/2 Wave Fix" column shows the additional number of stations that could be fixed by combining these two approaches. A similar set of tables are presented for the MFMG stations (Tables 24 through 41). The "Unfixable" stations in these tables were further analyzed to determine tower height increases necessary to bring these stations into compliance. Table 42 summarizes the impact for all 18 power density levels and Table 43 summarizes the effect of the mitigation strategies for single FM's on the ground. Bar graphs showing distances at which stations exceed the 18 exposure levels are presented in Appendix E.

These results represent the predicted impact to FM broadcast stations which would result from 18 alternative guidance levels. At the lowest level, 1 $\mu W/cm^2$, over 94 per cent of the stations would be affected. At the highest level studied, 10 mW/cm^2, less than 1 per cent would be affected. Assignments of cost to these impact levels are discussed in the Economic Impact report from Lawrence Livermore National Laboratory [1].

5. Impact on AM Stations

An AM broadcast antenna consists of one or more monopoles above ground. The ground plane is made more conductive by burying metal ground radials around the tower. The electrical heights of the towers may range from about 0.1 wavelength to one wavelength, the majority being less than 0.30 wavelength tall (see Figure 19). Multiple towers are sometimes used to produce nulls in the direction of other stations. The transmitted power may be 0.1, 0.25, 0.5, 1.0, 2.5, 5.0, 10.0, 25.0, or 50.0 kW (see Table 44) in accordance with FCC regulations [12].

TABLE 6. FM Modeling results for Guidance Level 1
(S = 1 uW/cm²)

# DAYS	# Stations > S	# stations brought below guidance level with:			UNFIXABLE
		ANTENNA FIX	1/2 WAVE FIX	ANTENNA AND 1/2 WAVE FIX	
1	66	25	0	0	41
2	295	113	32	27	123
3	628	229	197	69	133
4	515	132	223	42	116
5	162	19	37	14	92
6	369	20	111	43	195
7	92	15	47	5	25
8	176	11	80	23	62
9	14	0	10	1	3
10	221	0	76	59	86
11	20	0	12	5	3
12	311	2	222	48	39
13	3	1	2	0	0
14	31	0	28	1	2
16	5	1	4	0	0
TOTALS	2908	568	1081	337	922

TABLE 7. FM Modeling results for Guidance Level 2
(S = 10 uW/cm²)

# DAYS	# Stations > S	# stations brought below guidance level with:			UNFIXABLE
		ANTENNA FIX	1/2 WAVE FIX	ANTENNA AND 1/2 WAVE FIX	
1	41	12	14	3	12
2	223	76	118	5	24
3	513	369	122	1	21
4	436	267	148	1	20
5	142	28	83	4	27
6	341	56	241	1	43
7	82	39	36	0	7
8	160	30	120	0	10
9	14	1	11	0	2
10	204	9	180	2	13
11	20	1	19	0	0
12	270	35	230	2	3
13	3	2	1	0	0
14	21	10	11	0	0
16	2	2	0	0	0
TOTALS	2472	937	1334	19	182

TABLE 8. FM Modeling results for Guidance Level 3 (S = 20 uW/cm^2)

# DAYS	# Stations > S	# stations brought below guidance level with: ANTENNA FIX	1/2 WAVE FIX	ANTENNA AND 1/2 WAVE FIX	UNFIXABLE
1	29	13	9	1	6
2	146	62	72	2	10
3	318	241	64	3	10
4	311	218	79	3	11
5	123	36	66	3	18
6	300	93	181	6	20
7	63	34	26	0	3
8	141	39	95	0	7
9	13	4	7	1	1
10	192	43	144	2	3
11	20	9	11	0	0
12	239	103	134	0	2
13	2	2	0	0	0
14	20	13	7	0	0
16	0	0	0	0	0
TOTALS	1917	910	895	21	91

TABLE 9. FM Modeling results for Guidance Level 4 (S = 50 uW/cm^2)

# DAYS	# Stations > S	# stations brought below guidance level with: ANTENNA FIX	1/2 WAVE FIX	ANTENNA AND 1/2 WAVE FIX	UNFIXABLE
1	11	5	1	2	3
2	69	33	35	0	1
3	122	82	32	2	6
4	153	106	41	2	4
5	90	36	44	2	8
6	227	126	93	1	7
7	41	25	16	0	0
8	105	61	42	1	1
9	7	4	3	0	0
10	163	85	77	0	1
11	18	15	3	0	0
12	187	141	46	0	0
13	1	1	0	0	0
14	12	9	3	0	0
16	0	0	0	0	0
TOTALS	1206	729	436	10	31

TABLE 10. FM Modeling results for Guidance Level 5
(S = 75 $\mu W/cm^2$)

# BAYS	# Stations > S	# stations brought below guidance level with:			UNFIXABLE
		ANTENNA FIX	1/2 WAVE FIX	ANTENNA AND 1/2 WAVE FIX	
1	7	1	3	1	2
2	41	13	27	1	0
3	72	44	22	1	5
4	103	69	31	0	3
5	83	43	35	0	5
6	198	128	64	0	6
7	32	21	11	0	0
8	94	63	30	0	1
9	7	4	3	0	0
10	151	99	52	0	0
11	17	17	0	0	0
12	170	144	26	0	0
13	1	1	0	0	0
14	7	6	1	0	0
16	0	0	0	0	0
	-----	-----	-----	-----	-----
TOTALS	983	653	305	3	22

TABLE 11. FM Modeling results for Guidance Level 6
(S = 100 $\mu W/cm^2$)

# BAYS	# Stations > S	# stations brought below guidance level with:			UNFIXABLE
		ANTENNA FIX	1/2 WAVE FIX	ANTENNA AND 1/2 WAVE FIX	
1	6	1	4	0	1
2	35	13	22	0	0
3	59	38	16	1	4
4	81	55	24	0	2
5	72	38	29	1	4
6	172	113	56	2	1
7	30	19	11	0	0
8	89	63	26	0	0
9	7	4	3	0	0
10	145	102	43	0	0
11	16	16	0	0	0
12	159	143	16	0	0
13	1	1	0	0	0
14	6	5	1	0	0
16	0	0	0	0	0
	-----	-----	-----	-----	-----
TOTALS	878	611	251	4	12

TABLE 12. FM Modeling results for Guidance Level 7
(S = 200 uW/cm^2)

# BAYS	# Stations > S	# stations brought below guidance level with:			UNFIXABLE
		ANTENNA FIX	1/2 WAVE FIX	ANTENNA AND 1/2 WAVE FIX	
1	5	3	2	0	0
2	19	10	9	0	0
3	30	19	10	0	1
4	43	26	16	0	1
5	48	26	22	0	0
6	111	76	34	1	0
7	23	15	8	0	0
8	68	52	16	0	0
9	3	1	2	0	0
10	107	84	23	0	0
11	9	9	0	0	0
12	90	85	5	0	0
13	0	0	0	0	0
14	4	4	0	0	0
16	0	0	0	0	0
	-----	-----	-----	-----	-----
TOTALS	560	410	147	1	2

TABLE 13. FM Modeling results for Guidance Level 8
(S = 300 uW/cm^2)

# BAYS	# Stations > S	# stations brought below guidance level with:			UNFIXABLE
		ANTENNA FIX	1/2 WAVE FIX	ANTENNA AND 1/2 WAVE FIX	
1	4	3	1	0	0
2	10	6	4	0	0
3	22	13	8	1	0
4	28	16	12	0	0
5	40	27	13	0	0
6	75	54	21	0	0
7	15	9	6	0	0
8	44	35	9	0	0
9	2	0	2	0	0
10	83	66	17	0	0
11	6	6	0	0	0
12	68	65	3	0	0
13	0	0	0	0	0
14	3	3	0	0	0
16	0	0	0	0	0
	-----	-----	-----	-----	-----
TOTALS	400	303	96	1	0

TABLE 14. FM Modeling results for Guidance Level 9
(S = 400 uW/cm^2)

# BAYS	# Stations > S	# stations brought below guidance level with: ANTENNA FIX	1/2 WAVE FIX	ANTENNA AND 1/2 WAVE FIX	UNFIXABLE
1	1	1	0	0	0
2	4	2	2	0	0
3	18	12	6	0	0
4	20	11	9	0	0
5	34	23	11	0	0
6	61	45	16	0	0
7	12	7	5	0	0
8	32	23	9	0	0
9	2	1	1	0	0
10	55	44	11	0	0
11	3	3	0	0	0
12	36	34	2	0	0
13	0	0	0	0	0
14	2	2	0	0	0
16	0	0	0	0	0
TOTALS	280	208	72	0	0

TABLE 15. FM Modeling results for Guidance Level 10
(S = 500 uW/cm^2)

# BAYS	# Stations > S	# stations brought below guidance level with: ANTENNA FIX	1/2 WAVE FIX	ANTENNA AND 1/2 WAVE FIX	UNFIXABLE
1	0	0	0	0	0
2	3	2	1	0	0
3	15	9	6	0	0
4	16	9	7	0	0
5	28	17	11	0	0
6	50	38	12	0	0
7	9	6	3	0	0
8	24	17	7	0	0
9	2	1	1	0	0
10	47	40	7	0	0
11	2	2	0	0	0
12	27	25	2	0	0
13	0	0	0	0	0
14	2	2	0	0	0
16	0	0	0	0	0
TOTALS	225	168	57	0	0

TABLE 16. FM Modeling results for Guidance Level 11
(S = 600 uW/cm²)

		# stations brought below guidance level with:			
# BAYS	# Stations > S	ANTENNA FIX	1/2 WAVE FIX	ANTENNA AND 1/2 WAVE FIX	UNFIXABLE
1	0	0	0	0	0
2	3	3	0	0	0
3	13	8	5	0	0
4	13	8	5	0	0
5	25	17	8	0	0
6	39	31	8	0	0
7	6	4	2	0	0
8	20	13	7	0	0
9	2	1	1	0	0
10	39	34	5	0	0
11	2	2	0	0	0
12	24	22	2	0	0
13	0	0	0	0	0
14	2	2	0	0	0
16	0	0	0	0	0
	-----	-----	-----	-----	-----
TOTALS	188	145	43	0	0

TABLE 17. FM Modeling results for Guidance Level 12
(S = 700 uW/cm²)

		# stations brought below guidance level with:			
# BAYS	# Stations > S	ANTENNA FIX	1/2 WAVE FIX	ANTENNA AND 1/2 WAVE FIX	UNFIXABLE
1	0	0	0	0	0
2	1	1	0	0	0
3	12	7	5	0	0
4	13	8	5	0	0
5	22	14	8	0	0
6	37	29	8	0	0
7	6	4	2	0	0
8	16	9	7	0	0
9	2	1	1	0	0
10	30	29	1	0	0
11	0	0	0	0	0
12	18	17	1	0	0
13	0	0	0	0	0
14	1	1	0	0	0
16	0	0	0	0	0
	-----	-----	-----	-----	-----
TOTALS	158	120	38	0	0

TABLE 18. FM Modeling results for Guidance Level 13 (S = 800 uW/cm^2)

# BAYS	# Stations > S	# stations brought below guidance level with:			UNFIXABLE
		ANTENNA FIX	1/2 WAVE FIX	ANTENNA AND 1/2 WAVE FIX	
1	0	0	0	0	0
2	1	1	0	0	0
3	12	8	4	0	0
4	12	7	5	0	0
5	21	14	7	0	0
6	31	25	6	0	0
7	6	5	1	0	0
8	14	8	6	0	0
9	2	1	1	0	0
10	27	26	1	0	0
11	0	0	0	0	0
12	15	14	1	0	0
13	0	0	0	0	0
14	1	1	0	0	0
16	0	0	0	0	0
	-----	-----	-----	-----	-----
TOTALS	142	110	32	0	0

TABLE 19. FM Modeling results for Guidance Level 14 (S = 900 uW/cm^2)

# BAYS	# Stations > S	# stations brought below guidance level with:			UNFIXABLE
		ANTENNA FIX	1/2 WAVE FIX	ANTENNA AND 1/2 WAVE FIX	
1	0	0	0	0	0
2	1	1	0	0	0
3	10	6	4	0	0
4	11	7	4	0	0
5	19	13	6	0	0
6	28	22	6	0	0
7	6	5	1	0	0
8	11	7	4	0	0
9	2	1	1	0	0
10	23	22	1	0	0
11	0	0	0	0	0
12	12	11	1	0	0
13	0	0	0	0	0
14	1	1	0	0	0
16	0	0	0	0	0
	-----	-----	-----	-----	-----
TOTALS	124	96	28	0	0

TABLE 20. FM Modeling results for Guidance Level 15
(S = 1000 uW/cm²)

		# stations brought below guidance level with:			
# BAYS	# Stations > S	ANTENNA FIX	1/2 WAVE FIX	ANTENNA AND 1/2 WAVE FIX	UNFIXABLE
1	0	0	0	0	0
2	1	1	0	0	0
3	9	7	2	0	0
4	10	7	3	0	0
5	19	14	5	0	0
6	28	22	6	0	0
7	5	5	0	0	0
8	8	5	3	0	0
9	2	1	1	0	0
10	21	20	1	0	0
11	0	0	0	0	0
12	12	11	1	0	0
13	0	0	0	0	0
14	1	1	0	0	0
16	0	0	0	0	0
	-----	-----	-----	-----	-----
TOTALS	116	94	22	0	0

TABLE 21. FM Modeling results for Guidance Level 16
(S = 2000 uW/cm²)

		# stations brought below guidance level with:			
# BAYS	# Stations > S	ANTENNA FIX	1/2 WAVE FIX	ANTENNA AND 1/2 WAVE FIX	UNFIXABLE
1	0	0	0	0	0
2	0	0	0	0	0
3	8	7	1	0	0
4	4	2	2	0	0
5	11	8	3	0	0
6	17	16	1	0	0
7	3	3	0	0	0
8	3	2	1	0	0
9	1	1	0	0	0
10	8	7	1	0	0
11	0	0	0	0	0
12	3	3	0	0	0
13	0	0	0	0	0
14	1	1	0	0	0
16	0	0	0	0	0
	-----	-----	-----	-----	-----
TOTALS	59	50	9	0	0

TABLE 22. FM Modeling results for Guidance Level 17
(S = 5000 uW/cm^2)

# BAYS	# Stations > S	# stations brought below guidance level with:			UNFIXABLE
		ANTENNA FIX	1/2 WAVE FIX	ANTENNA AND 1/2 WAVE FIX	
1	0	0	0	0	0
2	0	0	0	0	0
3	4	4	0	0	0
4	0	0	0	0	0
5	2	2	0	0	0
6	4	4	0	0	0
7	1	1	0	0	0
8	2	2	0	0	0
9	0	0	0	0	0
10	2	2	0	0	0
11	0	0	0	0	0
12	0	0	0	0	0
13	0	0	0	0	0
14	0	0	0	0	0
16	0	0	0	0	0
	-----	-----	-----	-----	-----
TOTALS	15	15	0	0	0

TABLE 23. FM Modeling results for Guidance Level 18
(S = 10000 uW/cm^2)

# BAYS	# Stations > S	# stations brought below guidance level with:			UNFIXABLE
		ANTENNA FIX	1/2 WAVE FIX	ANTENNA AND 1/2 WAVE FIX	
1	0	0	0	0	0
2	0	0	0	0	0
3	1	1	0	0	0
4	0	0	0	0	0
5	0	0	0	0	0
6	1	1	0	0	0
7	0	0	0	0	0
8	1	1	0	0	0
9	0	0	0	0	0
10	0	0	0	0	0
11	0	0	0	0	0
12	0	0	0	0	0
13	0	0	0	0	0
14	0	0	0	0	0
16	0	0	0	0	0
	-----	-----	-----	-----	-----
TOTALS	3	3	0	0	0

TABLE 24. FM Modeling results for Guidance Level 1
(S = 1 uW/cm²)

		# Stations brought below guidance level with:		
# BAYS	# Stations > S	ANTENNA FIX	1/2 WAVE FIX	UNFIXABLE
1	8	0	0	8
2	48	10	19	19
3	42	2	9	31
4	47	2	7	38
5	26	1	1	24
6	53	0	5	48
7	10	0	4	6
8	39	0	13	26
9	4	0	4	0
10	25	0	5	20
11	1	0	1	0
12	31	0	22	9
13	0	0	0	0
14	9	0	9	0
15	0	0	0	0
16	5	0	4	1
TOTALS	348	15	103	230
SITES	148	51		97

TABLE 25. FM Modeling results for Guidance Level 2
(S = 10 uW/cm²)

		# Stations brought below guidance level with:		
# BAYS	# Stations > S	ANTENNA FIX	1/2 WAVE FIX	UNFIXABLE
1	6	0	1	5
2	24	8	11	5
3	35	8	15	12
4	39	7	9	23
5	25	1	10	14
6	51	9	18	24
7	9	2	3	4
8	35	5	19	11
9	3	0	3	0
10	23	1	13	9
11	1	1	0	0
12	29	8	19	2
13	0	0	0	0
14	4	3	1	0
15	0	0	0	0
16	3	1	2	0
TOTALS	287	54	124	109
SITES	133	92		41

TABLE 26. FM Modeling results for Guidance Level 3
(S = 20 uW/cm^2)

# BAYS	# Stations > S	# Stations brought below guidance level with: ANTENNA FIX	1/2 WAVE FIX	UNFIXABLE
1	6	0	2	4
2	17	8	5	4
3	29	7	10	12
4	35	6	8	21
5	24	4	8	12
6	49	10	22	17
7	8	2	2	4
8	26	3	13	10
9	2	0	2	0
10	22	3	13	6
11	1	1	0	0
12	26	12	13	1
13	0	0	0	0
14	3	2	1	0
15	0	0	0	0
16	2	0	2	0
	-----	-----	-----	-----
TOTALS	250	58	101	91
SITES	117	83		34

TABLE 27. FM Modeling results for Guidance Level 4
(S = 50 uW/cm^2)

# BAYS	# Stations > S	# Stations brought below guidance level with: ANTENNA FIX	1/2 WAVE FIX	UNFIXABLE
1	5	2	3	0
2	9	5	1	3
3	22	5	9	8
4	31	6	10	15
5	23	7	9	7
6	44	16	21	7
7	7	3	2	2
8	19	5	10	4
9	0	0	0	0
10	18	7	6	5
11	1	1	0	0
12	20	14	6	0
13	0	0	0	0
14	2	2	0	0
15	0	0	0	0
16	1	1	0	0
	-----	-----	-----	-----
TOTALS	202	74	77	51
SITES	105	89		16

TABLE 28. FM Modeling results for Guidance Level 5 (S = 75 uW/cm²)

		# Stations brought below guidance level with:		
# BAYS	# Stations > S	ANTENNA FIX	1/2 WAVE FIX	UNFIXABLE
1	4	1	3	0
2	5	1	1	3
3	18	5	8	5
4	27	5	8	14
5	22	6	9	7
6	39	13	20	6
7	6	2	3	1
8	18	4	14	0
9	0	0	0	0
10	17	7	7	3
11	0	0	0	0
12	14	10	4	0
13	0	0	0	0
14	1	1	0	0
15	0	0	0	0
16	1	1	0	0
TOTALS	172	56	77	39
SITES	88	77		11

TABLE 29. FM Modeling results for Guidance Level 6 (S = 100 uW/cm²)

		# Stations brought below guidance level with:		
# BAYS	# Stations > S	ANTENNA FIX	1/2 WAVE FIX	UNFIXABLE
1	3	1	2	0
2	4	1	3	0
3	17	6	11	0
4	26	4	16	6
5	22	6	10	6
6	36	10	25	1
7	5	1	3	1
8	17	5	12	0
9	0	0	0	0
10	16	7	7	2
11	0	0	0	0
12	11	7	4	0
13	0	0	0	0
14	0	0	0	0
15	0	0	0	0
16	1	1	0	0
TOTALS	158	49	93	16
SITES	82	77		5

TABLE 30. FM Modeling results for Guidance Level 7
(S = 200 uW/cm²)

# BAYS	# Stations > S	# Stations brought below guidance level with: ANTENNA FIX	1/2 WAVE FIX	UNFIXABLE
1	1	1	0	0
2	2	1	1	0
3	13	3	10	0
4	20	3	13	4
5	14	1	10	3
6	27	10	17	0
7	3	1	2	0
8	12	4	8	0
9	0	0	0	0
10	15	8	7	0
11	0	0	0	0
12	7	6	1	0
13	0	0	0	0
14	0	0	0	0
15	0	0	0	0
16	1	1	0	0
	-----	-----	-----	-----
TOTALS	115	39	69	7
SITES	57	55		2

TABLE 31. FM Modeling results for Guidance Level 8
(S = 300 uW/cm²)

# BAYS	# Stations > S	# Stations brought below guidance level with: ANTENNA FIX	1/2 WAVE FIX	UNFIXABLE
1	0	0	0	0
2	1	0	1	0
3	13	3	10	0
4	20	5	15	0
5	13	3	10	0
6	22	9	13	0
7	2	0	2	0
8	10	4	6	0
9	0	0	0	0
10	13	9	4	0
11	0	0	0	0
12	6	5	1	0
13	0	0	0	0
14	0	0	0	0
15	0	0	0	0
16	1	1	0	0
	-----	-----	-----	-----
TOTALS	101	39	62	0
SITES	50	50		0

TABLE 32. FM Modeling results for Guidance Level 9
(S = 400 uW/cm²)

# BAYS	# Stations > S	# Stations brought below guidance level with: ANTENNA FIX	1/2 WAVE FIX	UNFIXABLE
1	0	0	0	0
2	1	0	1	0
3	11	3	8	0
4	20	6	14	0
5	12	3	9	0
6	18	9	9	0
7	2	0	2	0
8	7	2	5	0
9	0	0	0	0
10	12	9	3	0
11	0	0	0	0
12	6	5	1	0
13	0	0	0	0
14	0	0	0	0
15	0	0	0	0
16	1	1	0	0
	-----	-----	-----	-----
TOTALS	90	38	52	0
SITES	46	46		0

TABLE 33. FM Modeling results for Guidance Level 10
(S = 500 uW/cm²)

# BAYS	# Stations > S	# Stations brought below guidance level with: ANTENNA FIX	1/2 WAVE FIX	UNFIXABLE
1	0	0	0	0
2	1	0	1	0
3	11	4	7	0
4	16	5	11	0
5	12	4	8	0
6	16	9	7	0
7	2	0	2	0
8	7	2	5	0
9	0	0	0	0
10	12	9	3	0
11	0	0	0	0
12	6	5	1	0
13	0	0	0	0
14	0	0	0	0
15	0	0	0	0
16	1	1	0	0
	-----	-----	-----	-----
TOTALS	84	39	45	0
SITES	43	43		0

TABLE 34. FM Modeling results for Guidance Level 11
(S = 600 uW/cm²)

# DAYS	# Stations > S	# Stations brought below guidance level with: ANTENNA FIX	1/2 WAVE FIX	UNFIXABLE
1	0	0	0	0
2	1	0	1	0
3	10	5	5	0
4	15	5	10	0
5	12	4	8	0
6	14	8	6	0
7	2	0	2	0
8	5	1	4	0
9	0	0	0	0
10	10	8	2	0
11	0	0	0	0
12	4	4	0	0
13	0	0	0	0
14	0	0	0	0
15	0	0	0	0
16	0	0	0	0
	-----	-----	-----	-----
TOTALS	73	35	38	0
SITES	36	36		0

TABLE 35. FM Modeling results for Guidance Level 12
(S = 700 uW/cm²)

# DAYS	# Stations > S	# Stations brought below guidance level with: ANTENNA FIX	1/2 WAVE FIX	UNFIXABLE
1	0	0	0	0
2	1	1	0	0
3	9	5	4	0
4	12	5	7	0
5	11	4	7	0
6	11	7	4	0
7	2	1	1	0
8	5	1	4	0
9	0	0	0	0
10	8	7	1	0
11	0	0	0	0
12	3	3	0	0
13	0	0	0	0
14	0	0	0	0
15	0	0	0	0
16	0	0	0	0
	-----	-----	-----	-----
TOTALS	62	34	28	0
SITES	33	33		0

TABLE 36. FM Modeling results for Guidance Level 13
(S = 800 uW/cm^2)

		# Stations brought below guidance level with:		
# BAYS	# Stations > S	ANTENNA FIX	1/2 WAVE FIX	UNFIXABLE
1	0	0	0	0
2	1	1	0	0
3	9	6	3	0
4	12	5	7	0
5	11	4	7	0
6	11	7	4	0
7	2	1	1	0
8	4	1	3	0
9	0	0	0	0
10	8	7	1	0
11	0	0	0	0
12	3	3	0	0
13	0	0	0	0
14	0	0	0	0
15	0	0	0	0
16	0	0	0	0
	-----	-----	-----	-----
TOTALS	61	35	26	0
SITES	33	33		0

TABLE 37. FM Modeling results for Guidance Level 14
(S = 900 uW/cm^2)

		# Stations brought below guidance level with:		
# BAYS	# Stations > S	ANTENNA FIX	1/2 WAVE FIX	UNFIXABLE
1	0	0	0	0
2	1	1	0	0
3	7	5	2	0
4	12	5	7	0
5	10	5	5	0
6	11	7	4	0
7	2	1	1	0
8	4	1	3	0
9	0	0	0	0
10	7	6	1	0
11	0	0	0	0
12	3	3	0	0
13	0	0	0	0
14	0	0	0	0
15	0	0	0	0
16	0	0	0	0
	-----	-----	-----	-----
TOTALS	57	34	23	0
SITES	29	29		0

TABLE 38. FM Modeling results for Guidance Level 15
(S = 1000 uW/cm²)

# BAYS	# Stations > S	# Stations brought below guidance level with:		UNFIXABLE
		ANTENNA FIX	1/2 WAVE FIX	
1	0	0	0	0
2	1	1	0	0
3	6	5	1	0
4	12	6	6	0
5	10	5	5	0
6	10	7	3	0
7	2	1	1	0
8	3	2	1	0
9	0	0	0	0
10	6	5	1	0
11	0	0	0	0
12	3	3	0	0
13	0	0	0	0
14	0	0	0	0
15	0	0	0	0
16	0	0	0	0
	-----	-----	-----	-----
TOTALS	53	35	18	0
SITES	28	28		0

TABLE 39. FM Modeling results for Guidance Level 16
(S = 2000 uW/cm²)

# BAYS	# Stations > S	# Stations brought below guidance level with:		UNFIXABLE
		ANTENNA FIX	1/2 WAVE FIX	
1	0	0	0	0
2	1	1	0	0
3	1	1	0	0
4	5	2	3	0
5	6	5	1	0
6	6	5	1	0
7	2	1	1	0
8	3	3	0	0
9	0	0	0	0
10	2	2	0	0
11	0	0	0	0
12	0	0	0	0
13	0	0	0	0
14	0	0	0	0
15	0	0	0	0
16	0	0	0	0
	-----	-----	-----	-----
TOTALS	26	20	6	0
SITES	19	19		0

TABLE 40. FM Modeling results for Guidance Level 17 (S = 5000 uW/cm²)

# DAYS	# Stations > S	# Stations brought below guidance level with:		UNFIXABLE
		ANTENNA FIX	1/2 WAVE FIX	
1	0	0	0	0
2	0	0	0	0
3	0	0	0	0
4	2	2	0	0
5	2	2	0	0
6	1	1	0	0
7	1	1	0	0
8	2	2	0	0
9	0	0	0	0
10	0	0	0	0
11	0	0	0	0
12	0	0	0	0
13	0	0	0	0
14	0	0	0	0
15	0	0	0	0
16	0	0	0	0
TOTALS	8	8	0	0
SITES	6	6		0

TABLE 41. FM Modeling results for Guidance Level 18 (S = 10000 uW/cm²)

# DAYS	# Stations > S	# Stations brought below guidance level with:		UNFIXABLE
		ANTENNA FIX	1/2 WAVE FIX	
1	0	0	0	0
2	0	0	0	0
3	0	0	0	0
4	0	0	0	0
5	0	0	0	0
6	0	0	0	0
7	0	0	0	0
8	0	0	0	0
9	0	0	0	0
10	0	0	0	0
11	0	0	0	0
12	0	0	0	0
13	0	0	0	0
14	0	0	0	0
15	0	0	0	0
16	0	0	0	0
TOTALS	0	0	0	0
SITES	0	0		0

TABLE 42. SUMMARY OF NUMBERS OF FM RADIO STATIONS EXCEEDING POWER DENSITY LEVELS

Power Density Level μW/cm²	Single Stations on Ground		Multiple Sites on Ground		Single Stations on Buildings		Multiple Sites on Buildings		All Sites	
10,000	3	0.1	0	0.0	14	3.5	6	37.5	23	0.6
5,000	15	0.5	6	4.0	29	7.2	9	56.3	59	1.6
2,000	59	1.9	19	12.7	51	12.7	11	68.8	140	3.8
1,000	116	3.7	28	18.7	76	18.9	13	81.3	233	6.4
900	124	4.0	29	19.3	83	20.6	14	87.5	250	6.8
800	142	4.6	33	22.0	88	21.9	14	87.5	277	7.6
700	158	5.1	33	22.0	99	24.6	15	93.8	304	8.3
600	188	6.1	36	24.0	107	26.6	15	93.8	345	9.4
500	225	7.3	43	28.7	116	28.9	15	93.8	399	10.8
400	280	9.0	46	30.7	134	33.3	15	93.8	475	13.0
300	400	12.9	50	33.3	154	38.3	15	93.8	619	16.9
200	560	18.1	57	38.0	173	43.0	15	93.8	805	22.0
100	878	28.4	82	54.7	195	48.5	15	93.8	1170	31.9
75	983	31.8	88	58.7	211	52.5	15	93.8	1297	35.4
50	1206	39.0	105	70.0	227	56.5	15	93.8	1553	42.4
20	1917	61.9	117	78.0	275	68.4	15	93.8	2324	63.4
10	2472	79.9	133	88.7	325	80.8	15	93.8	2945	80.4
1	2908	94.0	148	98.7	389	96.8	15	93.8	3460	94.5
Totals	3095		150		402		16		3663	

TABLE 43. SUMMARY OF MODEL RESULTS TO EVALUATE DIFFERENT MITIGATION STRATEGIES FOR FM RADIO STATIONS

Power Density Level in μW/cm^2	Numbers of Stations Exceeding Power Density Levels Without Modification	With Change of Antenna	With one-half Wavelength Spacing
20,000	1	0	0
10,000	3	0	0
5,000	15	0	0
2,000	59	9	0
1,000	116	22	0
900	124	28	0
800	142	32	0
700	158	38	0
600	188	43	0
500	225	57	0
400	280	72	0
300	400	97	1
200	560	150	3
100	878	267	16
75	983	330	25
50	1206	477	41
20	1917	1007	112
10	2472	1535	201
1	2908	2340	1259

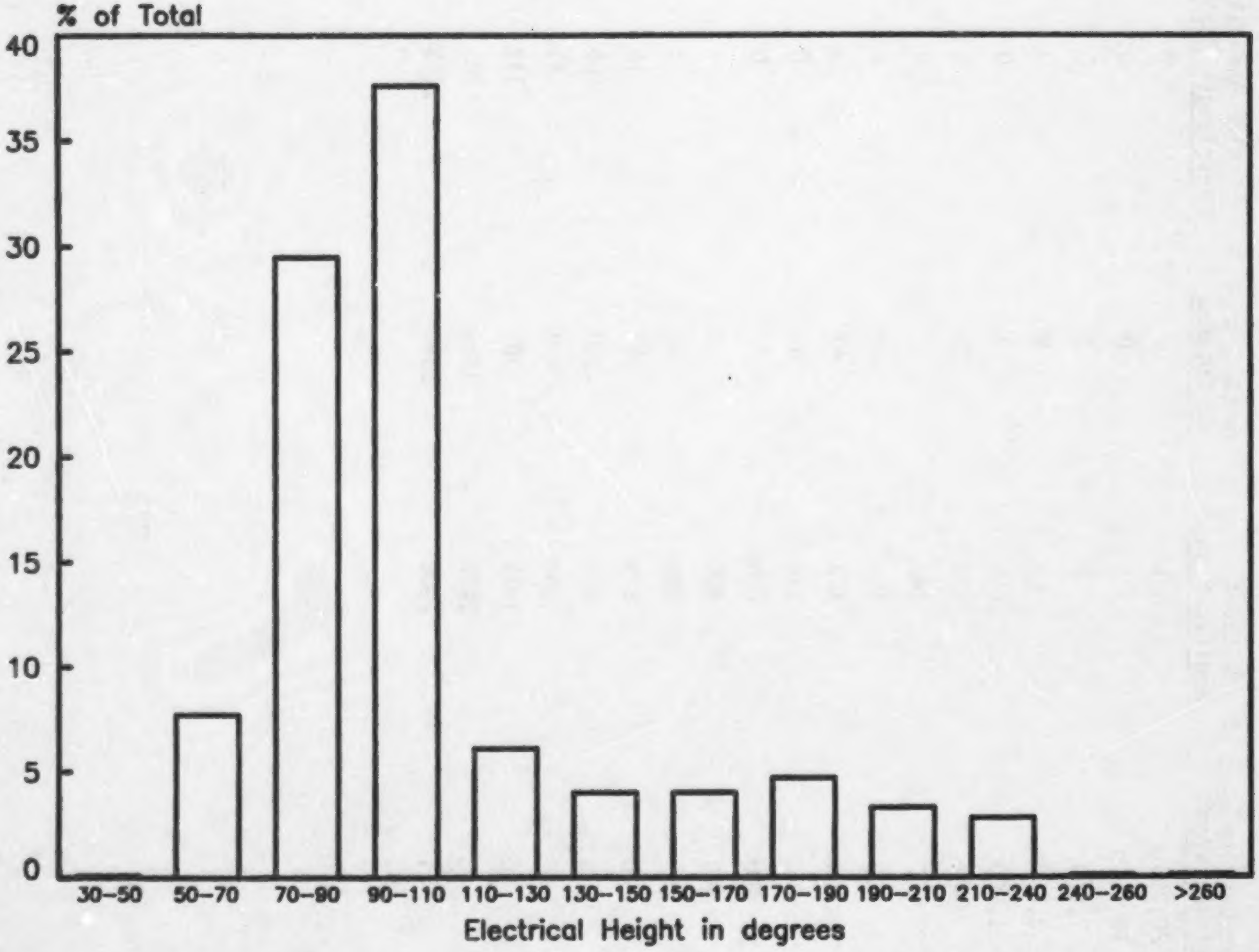

Figure 19. Distribution of physical electrical heights for stations in the AM data base.

TABLE 44. DISTRIBUTION OF TRANSMITTER POWERS FOR STATIONS IN THE AM DATA BASE

Transmitter Power	Number of Stations	Percent of Total
0.25	286	6.2
0.50	447	9.7
1.00	2,332	50.5
2.50	65	1.4
5.00	1,190	25.8
10.00	149	3.2
25.00	2	< 1.0
50.00	149	3.2

Three methods were examined for predicting fields around AM stations to use as a possible basis for an AM model. These three were a textbook theoretical approach [5], the LLNL Numerical Electromagnetic Code [7], and the "RADIAT" program developed by the FCC [13]. The requirements for the method chosen are that it accurately predict electric and magnetic fields in the near-field, properly add the component fields, and be relatively easy to apply to any power, electrical height, and frequency. The region in which the possible guidance levels might be exceeded extends to about 300 meters from the tower, much of which is within the near-field of the antenna.

The FCC "RADIAT" computer program is used to predict fields and other characteristics of any AM station in the FCC data base. It is designed to automatically retrieve the necessary data from the FCC's AM Engineering Data Base to be used in the calculations. Because of Radiat's availability, connection with the FCC AM data base, and its stated ability to predict near-fields, it was considered as a possible basis for an AM model. Examination of the output from RADIAT, however, revealed that it uses far-field equations to predict the fields no matter how close the calculation point is chosen to the tower. It is therefore inadequate for accurate modeling in the area of interest.

Theoretical approaches, such as the one described by Jordan and Balmain [5], assume a current distribution and then develop equations to predict the fields. These equations were automated in order to examine the results as a function of electrical height. Because a sinusoidal current distribution is assumed, this method predicts low electric fields around the base of the tower when the electrical height is an odd multiple of 0.25 wavelengths. At these electrical heights, the current is a maximum (and the voltage a minimum) at the base of the tower, resulting in low electric fields. Limited measurements around 0.25 wavelength tall AM towers do not show these low field levels. It is apparent that this idealized current distribution does not occur in typical AM broadcast systems.

The LLNL Numerical Electromagnetic Code (NEC) [7] was studied as a third approach to modeling AM transmitting antennas. It can be operated easily for AM towers since the geometry of the antenna is simple. NEC offers several advantages over the other techniques. It is structured to calculate fields at any point or set of points chosen and can be directed to use near-field equations when necessary. The output consists of electric and magnetic field components as well as the properly summed total fields at each point. This last feature is particularly important since the orthogonal field components in the near-field may differ in both magnitude and phase relationship and thus require complex techniques for determining the resultant fields.

NEC was found to agree quite well with the theoretical approach [5] discussed earlier for most cases. A notable exception is that the NEC results do not show the greatly reduced electric fields for 0.25 wavelength towers. Two possible reasons for this lack of agreement are that the current distribution predicted by NEC is calculated over each segment (20 segments were used to model AM towers) and the feed point was chosen at the bottom of the tower preventing zero voltage from occuring at this point. In reality most AM towers have an elevated feed point, sometimes several feet above the ground.

The NEC code was chosen to be used as the basis for an AM model because of its ease of use and other advantages discussed above. Fields as a function of distance were plotted from NEC runs for various electrical heights and frequencies in order to study trends. Several important characteristics were noticed. If the electrical height is held constant but the frequency varied, the electric fields will be higher over a certain range of distances for higher frequencies. This effect can be explained by noticing that ten meters at 600 kHz and 10 meters at 800 kHz are different relative distances. Since the towers are shorter at higher frequencies, the fields are expected to be higher. Another trend is that magnetic fields are typically but not always higher than electric fields in the near-field if a free-space comparison is used. In other words, the magnetic field can be converted to "free-space equivalent" electric field using $E_{eq} = H*377$ for comparison. Magnetic fields must therefore be considered as a possible limiting factor from a guidance point of view. When fields from towers of various electrical heights were compared, it was obvious that a simple trend could not be established with regard to electrical height. Fields may increase or decrease as electrical height is increased. All of the comparison runs were performed holding the input power constant.

The AM model was developed using the considerations discussed above. In summary, fields may be higher for higher frequencies (holding electrical height constant), magnetic fields may be higher than electric fields from a guidance viewpoint, and no simple trend can be established as a function of electrical height. The variety of parameters for a given station are frequency (540 to 1,600 kHz in 10 kHz increments), electrical height (< 0.1 wavelength to 1.0 wavelength), power (nine discrete values listed earlier), feed design, and array factors. We simplified the last two parameters by assuming a base feed and a single tower in all cases. The single tower assumption is reasonable since feeding all the power into a single tower generally results in higher fields immediately adjacent to the tower (within a few meters). The large number of AM stations considered and the time and cost involved in running NEC, eliminated the possibility of performing an exact modeling using NEC in each case. Instead, NEC was used on a set of discrete values comprising 60 possible configurations.

6 frequencies	0.6, 0.8, 1.0, 1.2, 1.4, 1.6 MHz
10 electrical heights	0.1, 0.2, 0.3, . . . 1.0 wavelengths

50 kW power was used in all cases

In each case, the total electric and magnetic fields were computed at four meter intervals ranging from 2 to 298 meters from the tower at a height of two meters above ground. Fields from AM stations do not vary significantly from the ground up to a few meters above ground. Data from each of these runs was stored for future use.

A computer program was written to find the farthest distance from each of the 60 configurations at which the eighteen alternative guidance levels were exceeded. The program functioned by stepping toward the tower and comparing the higher of the electric or magnetic field to the alternative guidance levels. This process was repeated with the field levels scaled for lower power stations. The fields at 100 meters from a 5 kW station, for example, would be $1/\sqrt{2}$ times the fields from a 10 kW station at 100 meters assuming the same tower configuration. In general:

$$E_2 = \sqrt{P_2/P_1} * E_1 \qquad (3)$$

where:
E_1 = field from station 1 at a given distance
E_2 = field from station 2 at the same distance
P_1 = broadcast power of station 1
P_2 = broadcast power of station 2

These distances were stored in a large, four dimensional mathematical array for easy access. The dimensions of this array are as follows:

Frequency	6
Electrical Height	10
Output Power	9
Guidance level	18

Thus the array consists of 9,720 distances corresponding to the above parameters. For example, the array point (1, 1, 1, 1) is the distance away from a 600 kHz, 0.1 wavelength, 0.1 kW station at which the fields drop below 10 V/m (E < 10 V/m and H*377 < 10 V/m).

Impact of the various guidance levels on the AM service was found using the above array. Each station in the AM data base was considered individually and its power, frequency, and electrical height used to choose distances from the array. In cases where the frequency was not one of the modeled values (0.6, 0.8, 1.0, 1.2, 1.4, 1.6 MHz), the next highest of the modeled values was used since field levels may increase at higher frequencies. For electrical heights other than those modeled, the distances for the next lower and next higher electrical heights were compared and the largest value was used. The result was that eighteen distances corresponding to the alternative guidance levels were assigned to each station, and then summarized in a table (Table 45) showing the numbers of stations requiring various property restrictions at each guidance level. The table also shows how many of these restricted areas are within the ground radials of the stations (estimated to be 0.25 wavelength long).

The results of the AM modeling are shown in Table 45. It is important to note that the 18 field strength levels in the row headings are different from the 18 alternative guidance levels examined for FM stations. The reason for this difference is that the proposed guidance levels for this frequency band are given in field strength units rather than power density units and are likely to be higher than the levels applicable to FM frequencies where maximum energy absorption rates in the human body occur. These AM field strength values were chosen to be a factor of five greater than those used for the VHF spectrum on account of these absorption differences. Distances shown in the table are in meters and the double entries in each row show the numbers of stations requiring fences to that distance and guidance level: 1) within the ground radials (estimated to be 0.25 wavelengths in length), and 2) beyond the ground radials. This table was provided to LLNL for economic analysis.

Examination of Table 45 shows that only at the lowest guidance levels do AM stations present a significant problem. Some stations would exceed the lowest level, 10 V/m, to distances of 280 meters from the tower. It is unlikely, however, that guidance levels this low would be recommended in the AM band since the body absorbs energy inefficiently at these frequencies. At field strength limits of 173 V/m and above, only a few stations can exceed the limit at distances greater than 20 meters. It should be possible to exclude public access to these areas with fences in most cases.

TABLE 45. NUMBERS OF AM STATIONS REQUIRING FENCES AT VARIOUS DISTANCES TO EXCLUDE AREAS IN WHICH FIELD STRENGTHS EXCEED 18 POSSIBLE GUIDANCE LEVELS. DOUBLE ENTRIES IN EACH ROW SHOW WHETHER THE REQUIRED FENCING DISTANCE IS WITHIN OR BEYOND THE EXTENT OF THE GROUND RADIALS (ESTIMATED TO BE ONE-QUARTER WAVELENGTH LONG)

Distance from tower (meters)		Field strength limits (V/m)																	
		10	31.6	44.7	70.8	86.6	100.0	141.3	173.2	200.0	223.9	244.9	264.6	281.8	300.0	316.2	446.7	708.0	1000.0
2–20	within	155	3249	3631	4389	4465	4502	4566	4619	4619	4619	4619	4619	4619	4620	4620	4621	4622	4622
	beyond	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
20–40	within	2744	1215	902	231	157	120	56	3	3	3	3	3	3	2	2	1		
	beyond	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		
40–60	within	342	68	71	2														
	beyond	57	0	17	0														
60–80	within	319	45																
	beyond	651	44																
80–100	within	60	1																
	beyond	17	0																
100–120	within	10																	
	beyond	116																	
120–140	within	0																	
	beyond	0																	
140–160	within	0																	
	beyond	1																	
160–180	within	0																	
	beyond	1																	
180–200	within	0																	
	beyond	0																	
200–220	within	0																	
	beyond	7																	
220–240	within	0																	
	beyond	102																	
240–260	within	0																	
	beyond	30																	
260–280	within	0																	
	beyond	10																	

*The field limits shown in the top row are those values which would correspond to the example radiation protection guidance frequency response curve illustrated in Figure 1 for frequencies less than 6 MHz (page 4).

Table 46 presents some of the same data as shown in Table 45 but with a finer resolution for distances close to the tower. This table provides a more detailed look at the fencing distances which would be required at the higher guidance levels. Entries in the "0 meters" row are stations which did not reach the field strength levels shown in the column headings at the closest calculation point (2 meters). Higher fields are possible closer to the tower. More information about the AM modeling results can be found in Appendix D.

6. Impact on TV Stations

Television broadcast antenna systems are similar to FM systems in that they typically consist of an array of radiating elements mounted on a tower. The elements of TV antennas, however, tend to be more complex in design and direct less energy towards the ground. The towers for these antennas are generally higher than FM towers, further reducing the net fields produced at ground level (see Figure 20). There are approximately 1,100 VHF and UHF licensed American TV stations in the FCC's TV Engineering Data Base, excluding low power stations. It was not possible to use the same modeling techniques for TV's that were used for FM stations because measured elevation patterns throughout 360 degrees of elevation for TV's were not available. Measurements of TV elevation patterns could not be performed within the time frame of this project. Instead, available information was examined to identify an alternative approach.

VHF and UHF antennas must be considered separately because of differences in their design and radiation patterns. Manual examination by EPA of a sample (approximately 10 percent) of the FCC TV physical files maintained at FCC headquarters revealed that the batwing element is most common for VHF broadcast. In the interest of time and simplicity, it was assumed for purposes of this study that all VHF TV antennas were of the batwing design. One reference by the inventor of this antenna contains some measured and calculated elevation patterns for a single element [14]. We compared these data to EPA field study data and a single measured elevation pattern obtained from one antenna manufacturer. These data indicated that batwing elements may radiate approximately 20 per cent as much in the downward direction as in the

TABLE 46. NUMBERS OF AM STATIONS REQUIRING FENCES AT VARIOUS DISTANCES TO EXCLUDE AREAS IN WHICH FIELD STRENGTHS EXCEED 18 POSSIBLE GUIDANCE LEVELS.

Distance from tower (meters)	Field strength limits (V/m)																	
	10.0	31.6	44.7	70.8	86.6	100.0	141.3	173.2	200.0	223.9	244.9	264.6	281.8	300.0	316.2	446.7	708.0	1000.0
0 - 2	0	0	1	76	129	431	909	1222	1241	2933	2960	3070	3075	3076	3098	3202	4251	4447
2 - 6	0	109	846	2680	2949	2673	2372	2947	2988	1440	1454	1362	1374	1375	1354	1305	368	0173
6 - 10	0	1093	1932	533	834	1125	1087	299	259	135	135	119	166	164	167	112	2	2
10 - 14	70	1799	591	962	448	194	140	84	131	111	70	68	4	5	1	2	1	0
14 - 18	85	248	261	138	105	79	6	57	1	2	2	2	2	1	1	1		
18 - 22	473	204	625	95	91	54	[illegible]	2	1	0	1	1	1	1	1			
22 - 26	382	684	130	59	0	48	1	0	1	1								
26 - 30	293	135	130	13	63	16	1	1	0	0								
30 - 34	1150	50	11	11	1	1												
34 - 38	446	142	6	53	1	1												
38 - 42	219	54	1	1	1													
42 - 46	40	5	15	0														
46 - 50	38	1	8	1														

*The field strength limits shown in the top row are those values which would correspond to the example radiation protection guidance frequency response curve illustrated in Figure 1 for frequencies less than 6 MHz (page 4).

**The numbers shown in the 0-2 meters row represent the number of AM stations not exceeding the specified field strength levels shown in the column headings, for distances up to 2 meters.

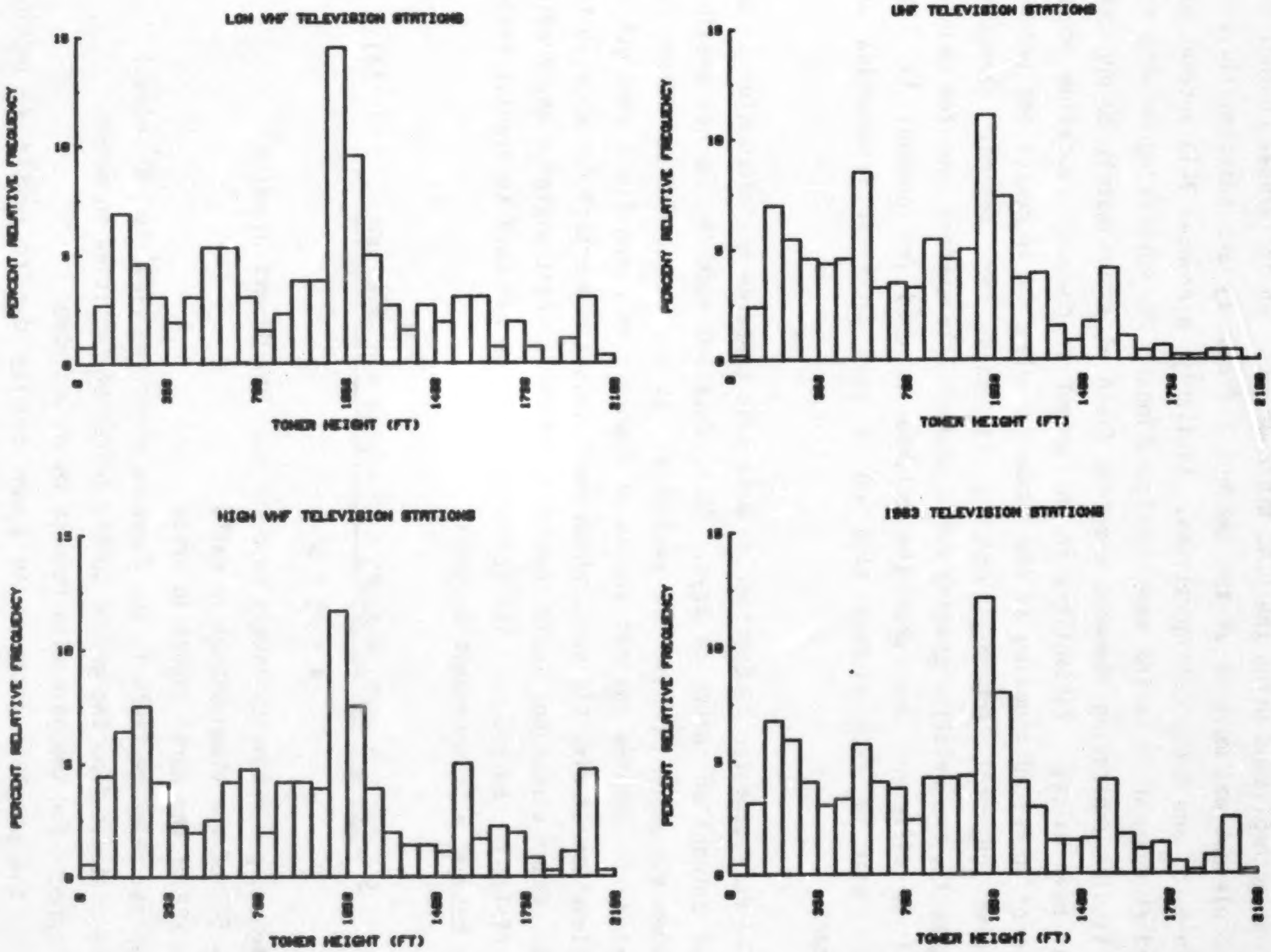

Figure 20. Distributions of tower heights for stations in the TV data base:

main beam in terms of relative field strength. As a more thorough check, extensive modeling of typical batwing elements when grouped in a broadcast array was accomplished using the LLNL NEC code [8]. An individual channel 2-3 antenna element was modeled at the channel 2 frequency and additionally when used in 4, 6, and 8 bay configurations. Similarly, a channel 7-13 antenna was modeled at channel 10 in the same configurations. The results agree with the other studies indicating downward electric field of approximately 20 per cent of main beam values. Variability in the amount of downward radiation occurs because of increased coupling as the number of elements increases and because the same physical interbay spacing is used for several channels. Consequently, the relative spacing for a channel 7-13 antenna used for channel 7 will be different than when the antenna is used for channel 13. The relative size of each element also varies when different frequencies are broadcast.

The FCC automated TV Engineering Data Base contains no information on the type of antenna or number of bays. Thus, detailed modeling is not possible even when elevation patterns are available. It was considered sufficient for this study to use the typical values of downward relative field strength at -90° elevation or directly down, which represents the shortest distance to the ground. Other directions would involve a greater transit distance and predict lower fields on the ground. The following equation was used to predict fields at the base of a TV broadcast antenna:

$$S = \frac{[(0.4 * VERP) + AERP] * F^2 * 2.56 * 1.64 * 100}{4 * PI * D^2} \qquad (4)$$

S = highest power density likely to occur near the ground in $\mu W/cm^2$
VERP = ERP of the video signal in watts
AERP = ERP of the aural signal in watts
F = typical relative field in the downward direction (-60° to -90° elev.)
D = the distance from the ground to the center of radiation in meters
1.64 corrects for the gain with respect to an isotrope
2.56 is the possible increase in power density due to ground reflections (assumes a field reflection coefficient of 1.6)

The factor of 0.4 appearing with the VERP corrects for the fact that TV stations video power is specified in terms of peak visual ERP and the 0.4 factor converts this to an RMS value for most practical conditions of video programming.

The aural ERP and tower height were added to the data base manually from the TV Factbook [2]. Tower heights listed in the Factbook (and FCC written files) are the height to the top of the tower and not to the antenna center of radiation. Examination of diagrams accompanying applications in the FCC written files showed the range of differences between these heights and the heights to the centers of radiation. Averaging these differences for low VHF, high VHF, and UHF stations gave the following correction factors:

D = T - 50 (ft)	(Low VHF)
D = T - 70	(High VHF)
D = T - 40	(UHF)

where: D = the height above ground of the center of radiation in feet
T = the overall height of the tower in feet

When utilizing these corrections in the model, a minimum tower height of less than 30 ft. was never permitted. This assumption was based on EPA field experience. In some cases, antennas may be mounted at other places on the tower instead of the tower top especially if several TV antennas are mounted on a single tower. However, this was impossible to determine for each case with available data. Experience has shown that TV antennas are usually located near, if not at the top of the tower. When FM antennas and TV antennas are mounted on the same tower, the TV antenna is normally found at the top.

The model uses a value of 18 percent relative field strength in the downward direction as compared to the main beam value. It also uses the shortest distance (straight down) and makes no allowance for fencing or exclusion of the area around the base of the tower. The presence of the tower itself will further reduce fields below the predicted values. In general, the model should tend to overestimate the impact of the guidance due to the above factors.

Various mitigation strategies were examined in order to determine which were the most practical and economical. After evaluating the effects of these possibilities and discussing them with industry consultants, it was decided that a change of antenna and/or an increase in tower height were the best choices of those which could be evaluated through modeling. Other methods such as fencing the area which exceeds the guidance may often be more economical, but are not amenable to modeling with available data. It was assumed that the least expensive, effective mitigation strategy would be chosen in each case. Thus, other alternatives such as fencing will reduce the impact of the guidance when they are feasible.

The concept of antenna change for TV's was not as straight forward as the similar case for FM stations since exact patterns for the various types of TV antennas were not available. As an alternative approach, the results of the NEC modeling of arrays of batwing elements were reviewed. At an interbay spacing of 0.833 for a six bay array these results show downward radiation as low as 10 percent of the main beam value on a relative field basis with very little reduction in main beam gain (Figures 21 and 22). Although a single element produces about 20 percent relative field in the downward direction, array coupling and interference effects can significantly reduce this value depending on the relative interbay spacing.

Since a single array with the same absolute interbay spacing can be used for any of several channels, the relative interbay spacing will depend on the frequency or channel at which the station is operating. The implication here is that an array can be custom designed to minimize downward radiation at any single channel. In order to verify the validity of this concept, the idea was discussed with a major TV antenna manufacturer. Engineers at this company indicated that they had in fact designed arrays as described above for the purpose of minimizing interference between their antenna and other antennas located below it. These custom antennas cost about 2.0 to 2.25 times the cost of a standard antenna. Using the above considerations, it was estimated that downward radiation of 7 per cent (field) of the main beam could be obtained.

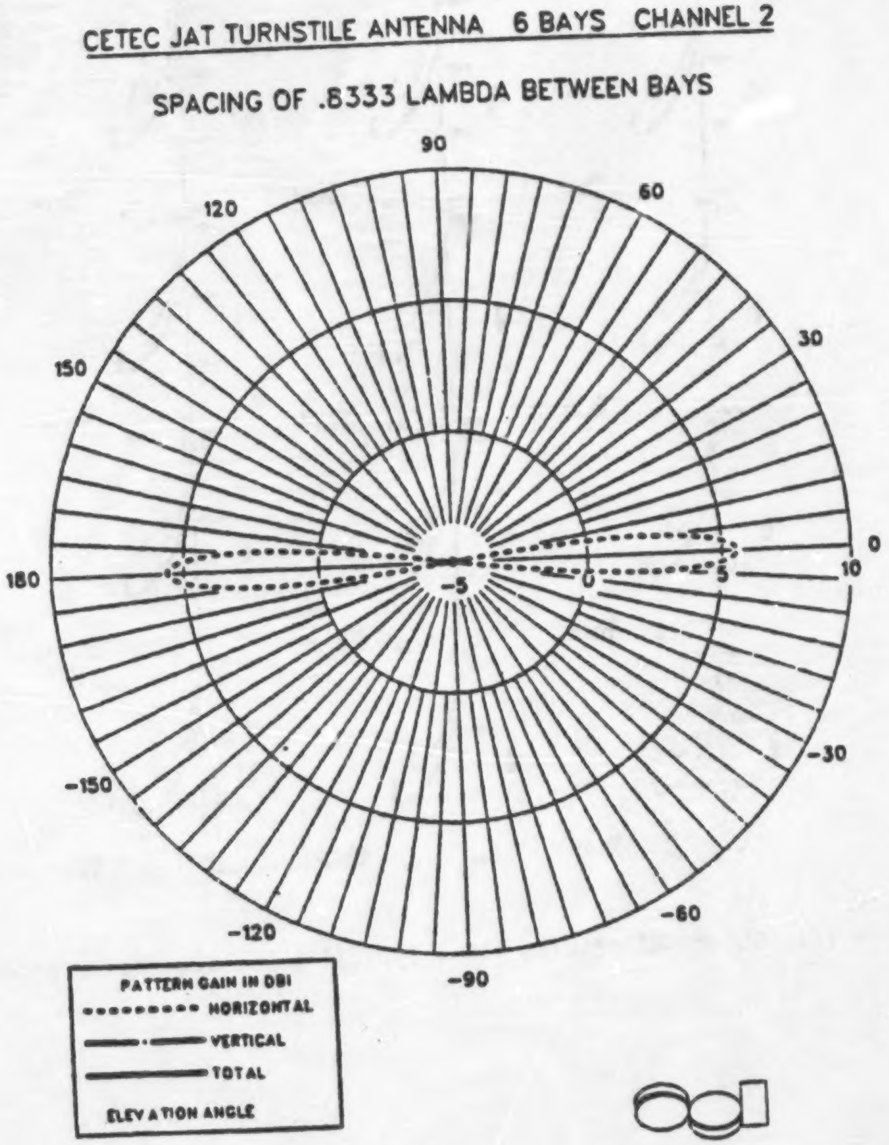

Figure 21. NEC model results for a typical 6-bay batwing TV antenna.

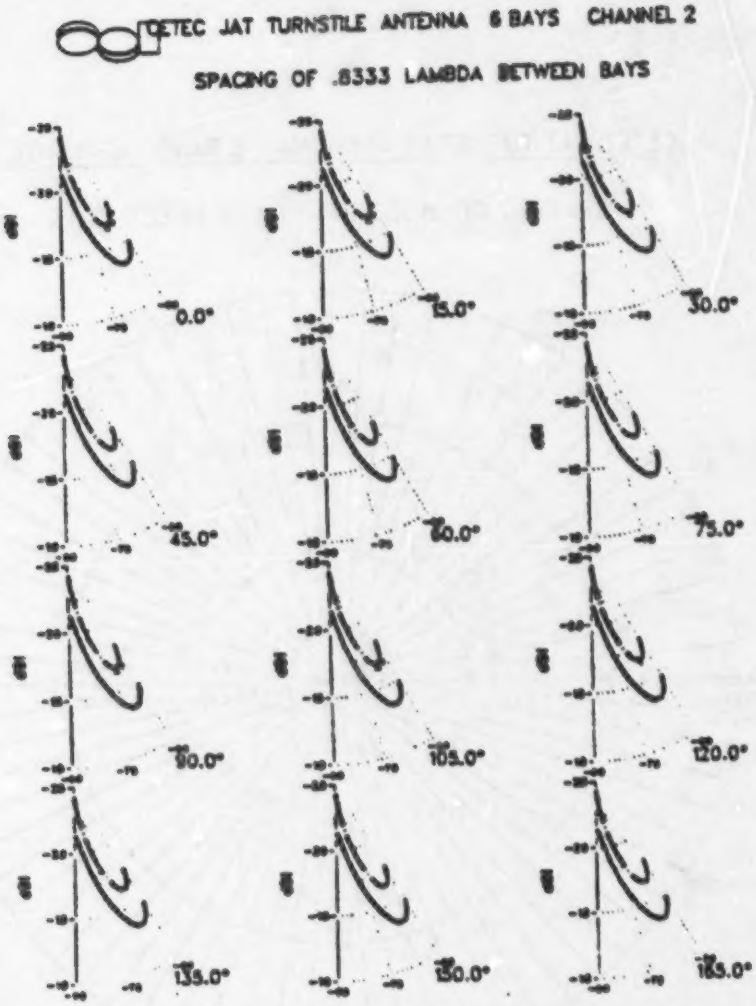

Figure 22. NEC model results for a typical 6-bay batwing TV antenna.

The second mitigation strategy was an increase in tower height. The minimum tower height necessary to bring a station below a given power density level was found using the following equation:

$$MTH = \sqrt{\frac{[(.4 * VERP) + AERP] * F^2 * 2.56 * 1.64 * 100}{4 * \pi * S}} \qquad (5)$$

where MTH = minimum tower height (ground to center of radiation) necessary to bring the station below a power density, S (same units as equation 4).

Prediction of the potential impact on VHF TV stations began with equation (4) to determine which stations would be likely to exceed a given alternative guidance level in their present configuration. The 18 guidance levels used for television stations were the same as those used for FM radio stations. This assumes that the frequency dependence of the proposed guidance is of the shape shown in Figure 1, i.e., a constant exposure limit from 30 to 1,000 MHz. Application of a ramp function for the guidance for frequencies greater than 300 MHz, similar to that used in the ANSI guide [15], would result in reduced impact compared to the results obtained with this approach. Fields from these stations were then re-calculated using equation (4) with F = 0.07 representing a change of antenna. A notation was made on each station file indicating for each alternative guidance level whether the station was already in compliance or could be brought into compliance with an antenna change. All stations predicted to exceed the guidance level were also subjected to equation (5) to determine the required tower height to bring the station into compliance. Equation (5) was then re-calculated with F = 0.07 to determine the increase in tower height required if the station employed both fixes. In other words, if a station required 500 feet of additional tower height to come into compliance with their present antenna, they may elect to purchase a new antenna and increase their tower height by a lesser amount. For the economic analysis, each TV station was analyzed to determine the minimum-cost compliance measure that would achieve the required reduction in field strength levels. Results of the TV analysis were provided to LLNL on magnetic tape in the form of tables. An example is shown below.

Sample of VHF TV stations exceeding 1 mW/cm^2

Present Tower Height	Compliance with Change of Antenna Only	New Tower Height Required without Change of Antenna	New Tower Height Required with Change of Antenna
54 ft.	Yes	255 ft.	54 ft.
90	No	322	170

UHF stations were modeled with the same equations as for VHF stations described above but using different values of F, the relative field strength in the downward direction. Values of F are not available in the manufacturer's literature at the large depression angles needed for this study and cannot be determined using wire codes such as the LLNL NEC because of the large surfaces involved in the antenna design. Slotted waveguide antennas, for example, cannot be accurately modeled using NEC. As an alternative approach, field study data were reviewed and this question was discussed with a major UHF antenna manufacturer. The manufacturer's engineers stated that typical values of F are about 10 percent and that some more expensive antennas have an F of about 5 percent. These values agreed with EPA's own measurements underneath operating UHF stations which indicated an F of less than 10 percent. Although the above information provides a limited basis for F for UHF antennas, it is reasonable that F should be small for these antennas for two reasons. First, UHF antennas have very high gain in the main beam indicating that a large portion of the transmitted energy is contained in this beam rather than other directions. Second, the large vertical surfaces incorporated in these antennas tend to eliminate downward radiation.

UHF stations were thus modeled using an F value of 10 per cent for stations in their present configuration and assuming that this value could be reduced to 5 percent by a change to an antenna of different design. As for VHF stations, the power density values at ground level were predicted at the present tower height with and without a change of antenna. The increases in tower height necessary to bring the stations into compliance at each guidance level were also calculated with and without a change of antenna.

The TV modeling results are shown in Table 47. The eighteen alternative power density levels are the same as those used for FM stations, but fewer TV stations are impacted than FM's at all power density levels. The number of potentially impacted TV stations drops off rapidly with increasing power density limits until zero impact is predicted for levels above 1,000 $\mu W/cm^2$. Cost analysis results are discussed in the economic impact report [1].

TABLE 47. NUMBERS OF TV STATIONS PREDICTED TO BE IMPACTED AT 18 POSSIBLE GUIDANCE LEVELS

Power Density Levels μW/cm^2	Number of Stations Predicted to Exceed Power Density Levels			Percentage of All TV's
	VHF	UHF	Total	
1	390	429	819	75.8
10	117	129	246	22.8
20	96	87	183	16.9
50	47	55	102	9.4
75	29	34	73	6.8
100	25	35	60	5.6
200	16	14	30	2.8
300	9	10	19	1.8
400	6	7	13	1.2
500	5	5	10	0.9
600	3	2	5	0.5
700	2	2	4	0.4
800	1	2	3	0.3
900	1	2	3	0.3
1,000	1	1	2	0.2
2,000	0	0	0	0.0
5,000	0	0	0	0.0
10,000	0	0	0	0.0

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Appendix A
Development of the FM Model

Section 1. Pattern measurements of FM antenna elements.

Complete elevation patterns for commercial FM broadcast antennas are not generally available. Only a few degrees of elevation pattern illustrating the shape of an antenna's main beam can be obtained from most manufacturers. Broadcasters have little interest in the rest of the elevation pattern since the energy transmitted outside of the main beam is seldom involved in the station's coverage. Strictly speaking, the complete elevation pattern is important in terms of efficiency. Energy that is directed outside of the main beam is wasted and may present a potential exposure problem.

The main beams of most FM antennas subtend less than 30 degrees and are directed approximately in the horizontal plane. Consequently, the energy in this beam intercepts the ground at distances ranging from several hundred to several thousand feet from the antenna. The exact distance will depend on beam width, tower height, beam tilt, and terrain. By the time this beam reaches the ground its power density is low, usually less than 10 $\mu W/cm^2$. Thus, in assessing the impact of alternative guidance levels, the main beam is not of major concern except at very low levels. It is worthwhile to note, however, that enforcement of alternative levels less than 10 $\mu W/cm^2$ would require a departure from the methods of FM broadcasting currently in use in the United States unless many stations were able to relocate to remote sites. Otherwise, the energy in the main beam of many broadcast stations would have to be reduced and radio coverage would be affected.

Guidance levels above 10 $\mu W/cm^2$ are generally only exceeded in areas near the broadcast tower and by energy outside of the main beam. Bringing a station into compliance with these guidance levels can be accomplished by changing factors other than the main beam. The audience coverage of the station can be maintained using the proper mitigation strategy. Figure (23) below shows the pattern for an array of one-half wave dipole elements. These elements are similar to those used in FM broadcasting, and help to illustrate the points discussed above.

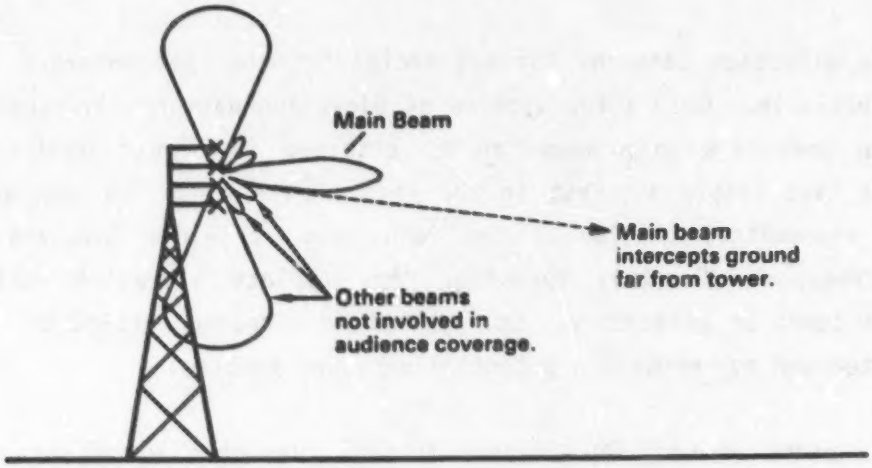

Main Beam
Main beam intercepts ground far from tower.
Other beams not involved in audience coverage.

Figure 23. The main beam of an FM broadcast antenna typically intercepts the ground at distances far from the tower.

The pattern of a real broadcast antenna consists of two components. These are an element pattern or the pattern of a single element when it is isolated from other elements, and an array pattern which results from addition of waves from an array of point sources. These two patterns must be multiplied together to obtain the total pattern of the antenna. Array patterns are easy to generate using geometry and phase considerations and are available in many textbooks. Element patterns, however cannot be predicted in any simple way.

Element patterns for five commonly used FM broadcast elements were measured via contract [6]. Measurements of the elements were performed to determine their elevation patterns in several configurations. These configurations were free space, side-mounted on a tower section, and leg-mounted on a tower section. The pattern of an element is partially dictated by the way it is mounted because of interactions with supporting metallic structures. By measuring the patterns in these three different configurations, it was possible to obtain some understanding of the pattern variations that may occur due to the variety of mounting configurations used by broadcasters.

The patterns were determined by rotating the elements and tower section on a 25 ft. dielectric support and recording the element's output while irradiating it with a reference antenna. This received pattern is the same as the element's transmitting pattern. The direction of rotation determined which pattern was recorded as shown in figure (24). Efforts were made to minimize ground reflections which can affect measurements and obscure the pattern.

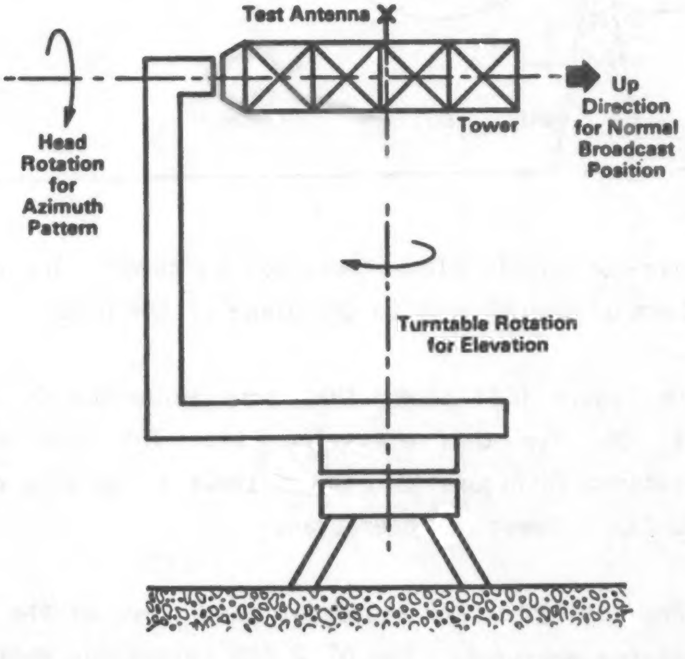

Test Antenna
Tower
Up Direction for Normal Broadcast Position
Head Rotation for Azimuth Pattern
Turntable Rotation for Elevation

Figure 24. Support configuration used to measure element patterns.

Patterns were measured in four elevation planes for each element in each configuration. Figure (25) below shows an elevation pattern superimposed on a sketch of a tower and single element. An elevation pattern can be thought of as a polar plot of field intensity in a vertical plane.

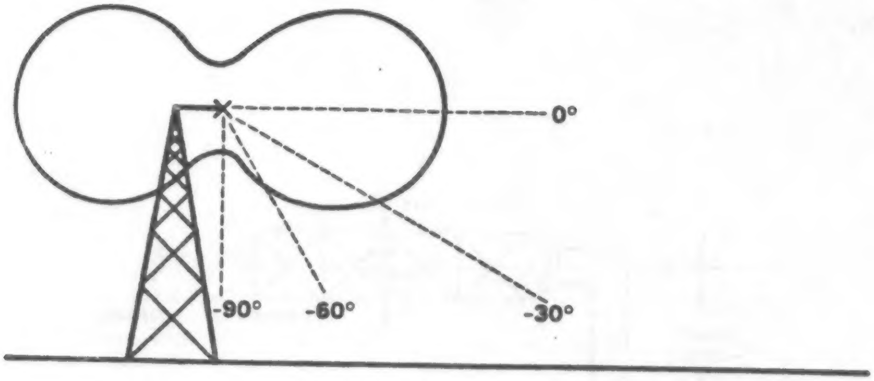


Figure 25. Side view of single element mounted on tower. The curved line is the elevation pattern of the element in the plane of the page.

The pattern in Figure (25) shows that more radiation is emitted at 0° elevation then at -90° for this elevation cut. The four elevation cuts measured are illustrated in Figure (26) which shows a top view of a broadcast element when mounted on a tower for operation.

The dashed lines in Figure (26) represent edge views of the planes of the four elevation patterns measured. The 0° - 180° elevation pattern (or cut), for example, shows the radiation emitted directly in front of and in back of the element. This is the pattern illustrated in the previous Figure. The 90° - 270° elevation pattern shows the radiation emitted to the sides of the element. Although the total pattern of an element is a three-dimensional solid angle plot of the element's radiation in all directions, these four elevation slices provide a good indication of the shape of the total pattern.

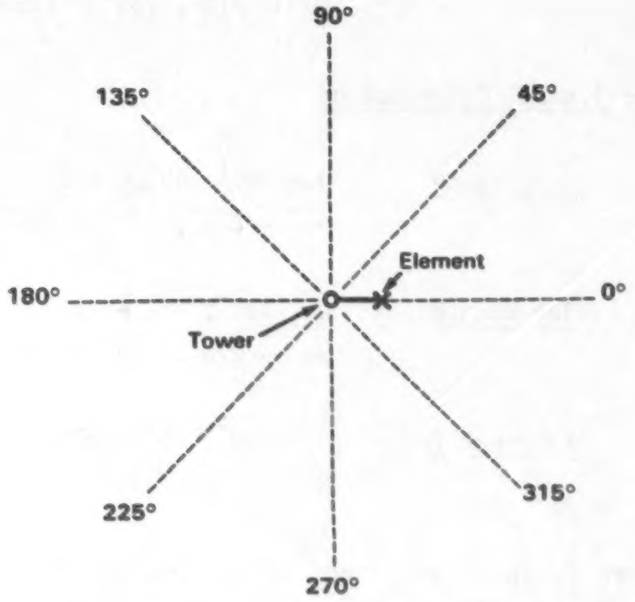


Figure 26. Top view of a single element mounted on a tower for broadcast. Dashed lines represent edge views of the elevation planes discussed in the text.

Both horizontally and vertically polarized signals were measured in each plane to fully characterize the elements. Thus, a total of 24 elevation patterns were found for each element as shown below.

Vertical polarization

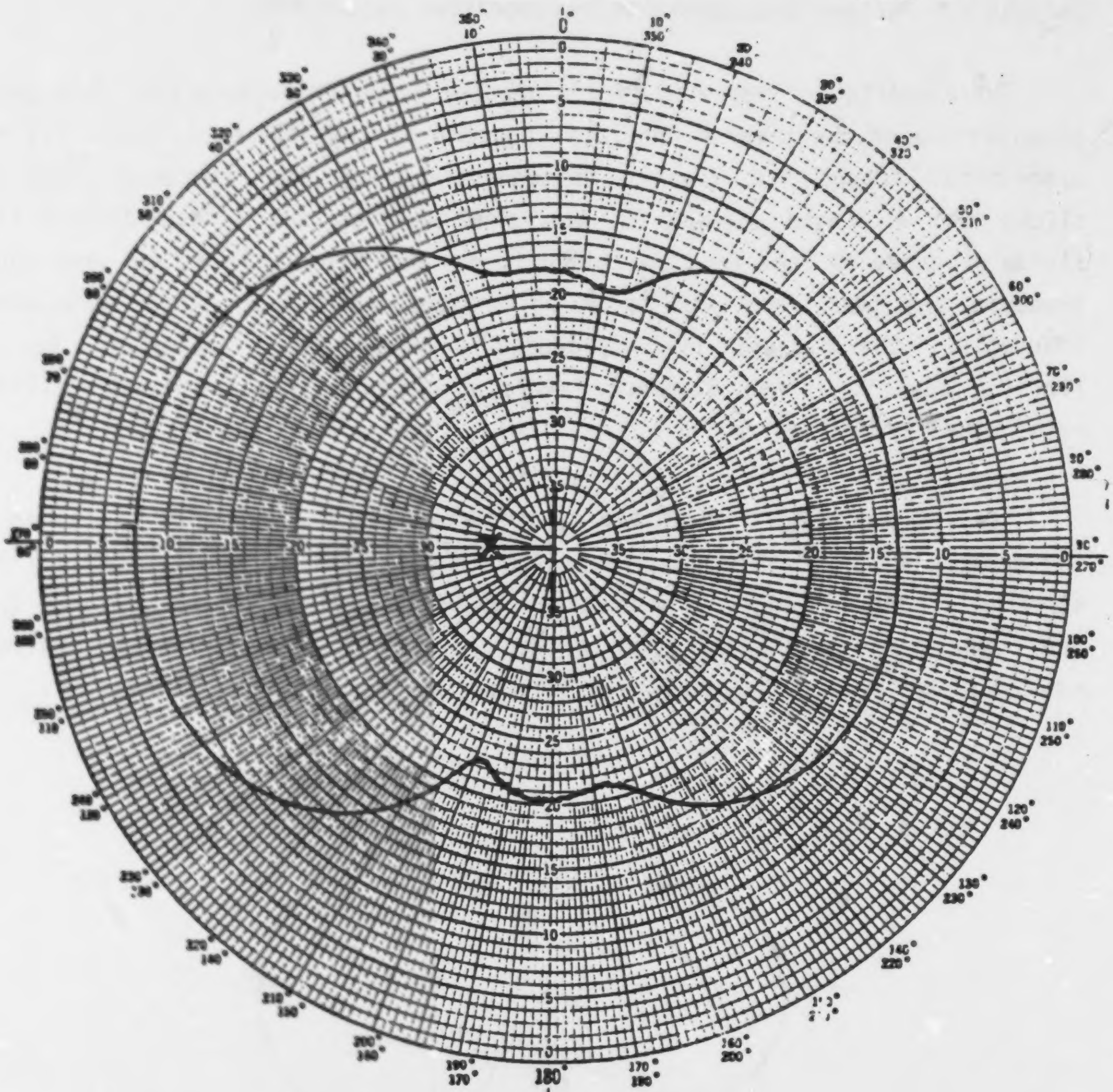
free space	0 - 180°, 45° - 225° 90° - 270°, 135° - 315°
leg-mounted	0 - 180°, 45° - 225° 90° - 270°, 135° - 315°

face mounted	0 - 180°, 45° - 225° 90° - 270°, 135° - 315°

Horizontal Polarization

free space	0 - 180°, 45° - 225° 90° - 270°, 135° - 315°
leg-mounted	0 - 180°, 45° - 225° 90° - 270°, 135° - 315°
face-mounted	0 - 180°, 45° - 225° 90° - 270°, 135° - 315°

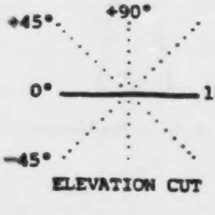
An example pattern is shown in Figure (27). See the final report to EPA contract number 68-03-3054 for the complete set of patterns and more details on the measurement methods [6].



PATTERN: ELEVATION

ANTENNA LOCATION
ON TOWER: FREE SPACE

TRANSMITTING ANTENNA
POLARIZATION: VERT.



HEIGHT OF TRANSMITTING
ANTENNA: 18.5 FT.

DIST. FROM TRANS. ANT.
TO TEST ANT.: 131 FT.

RING RADIUS: 27.5"

Figure 27. Measured elevation pattern of a single element.

Section 2 - Pattern Reduction for Incorporation in the Model

The electric and magnetic fields created by an FM antenna vary from point to point around the tower. The total pattern of the antenna is generally not symmetrical around the tower. Consequently, the four measured elevation slices for a single element in one configuration are shaped differently. Fields produced 10 feet from the tower in one direction will differ from those produced ten feet from the tower in another direction. From a Guidance standpoint, the highest field produced anywhere near the ground is the limiting quantity since Guidance levels dictate maximum permissible limits rather than typical values.

Prediction of the highest fields produced near the ground requires use of the worst elevation patterns. The pattern showing the highest relative field strength at a given angle will produce the highest field at the distance from the tower corresponding to that angle. Figure (28) below shows a single non-symmetric elevation pattern and antenna to illustrate this concept.

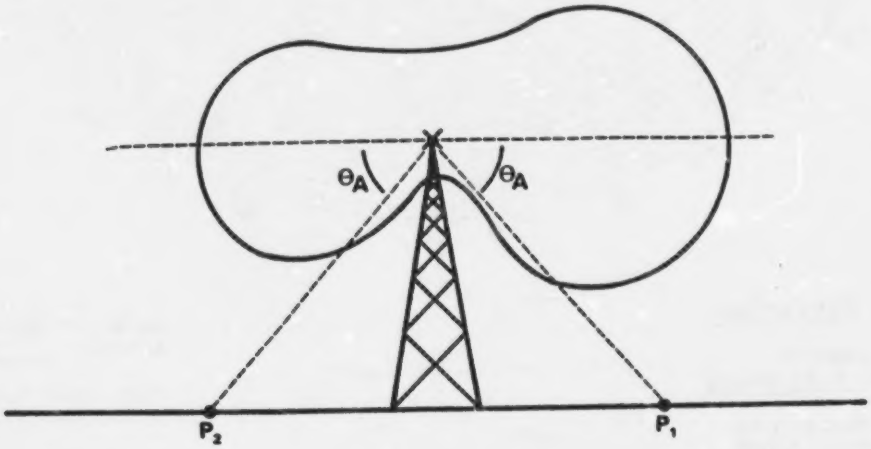


Figure 28. Although P_1 and P_2 are the same distance from the tower, fields at P_1 are more intense because of the shape of the element pattern.

At an angle θ_A from the horizon, the right-hand half of the pattern is more intense. Points P_1 and P_2 are the same distance from the tower but the field strength produced at P_1 is higher than that produced at P_2. The right-hand half of the pattern is the important one at angle θ_A from an impact point of view. At angle θ_B in Figure (29), the left hand half of the same pattern produces a greater field strength on the ground.

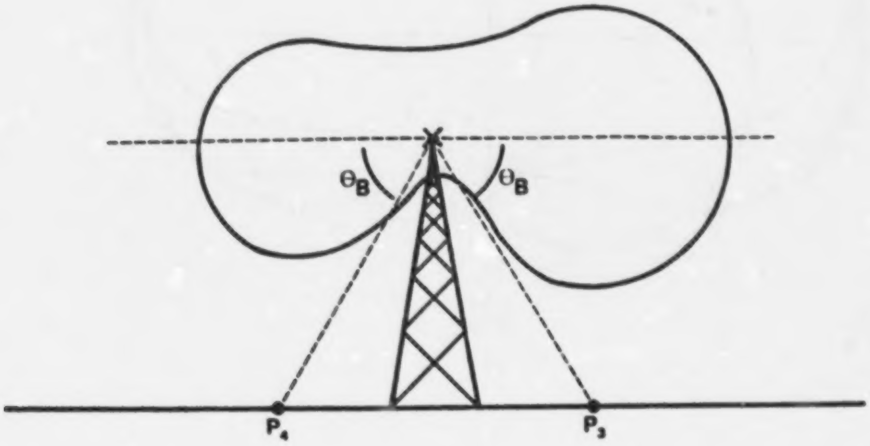


Figure 29. Fields are more intense at P_4 than at P_3.

Thus, for impact analysis, a model must use the highest value of relative field strength found among the available elevation patterns at each angle. These worst case values can be found by overlaying the elevation patterns and drawing an envelope as shown in Figure (30).

A single envelope pattern was constructed using the 12 elevation patterns for each polarization of each element. By combining these patterns for different directions and configurations, an approximation to the worst case fields likely to occur under actual broadcasting conditions was obtained. The final step in reducing these patterns was to combine the two halves of the envelope to produce an envelope pattern for a single direction away from the tower as shown in Figure (31).

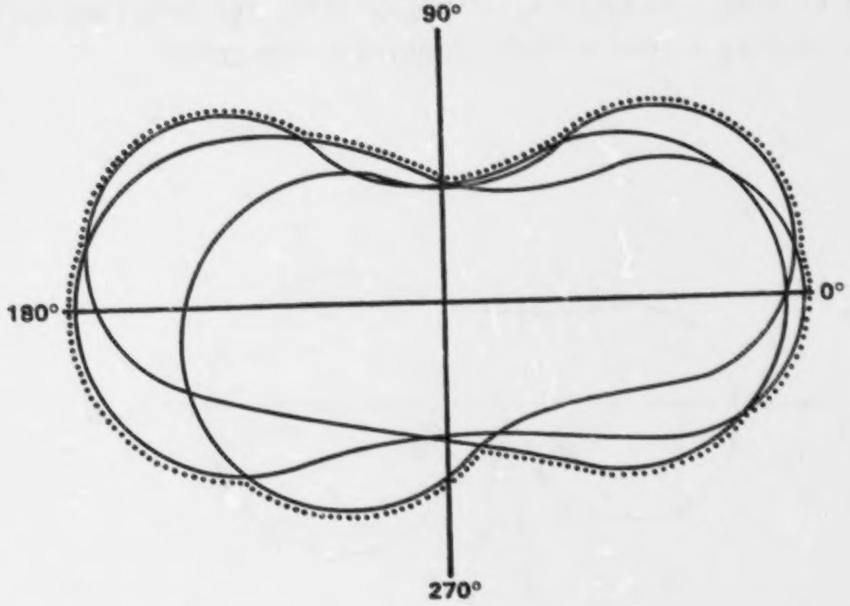


Figure 30. The dotted line illustrates the envelope of several elevation patterns of the same element.

Only the bottom half of this envelope was used in modeling since the top half is not involved in field levels on the ground. After the impact study was completed, it was found that the top half of the pattern can be important if the element is mounted upside down as is sometimes the case. However, the top and bottom halves of the final envelopes are similar in shape and the above oversight does not introduce a significant error.

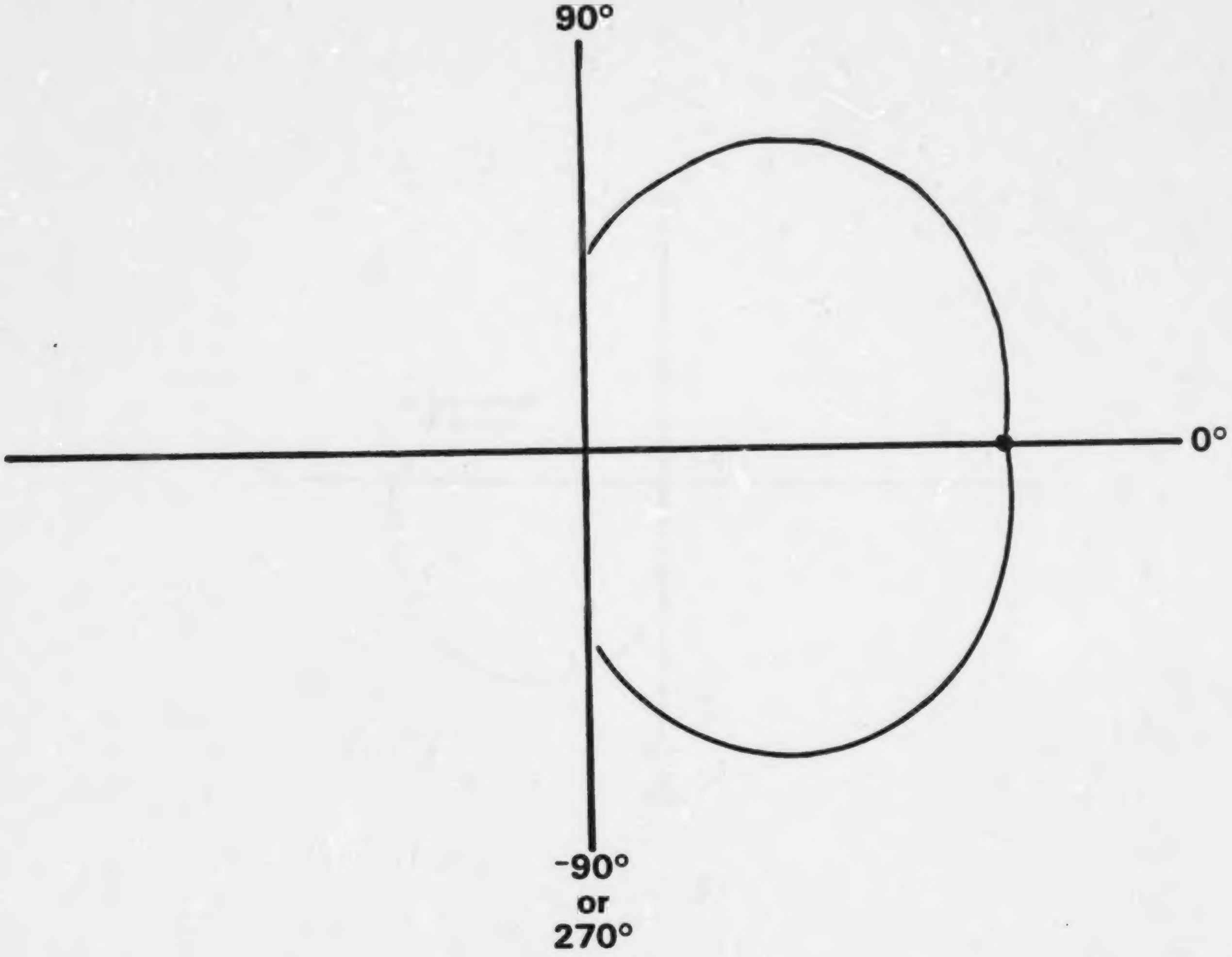


Figure 31. Envelope for a single direction away from the tower.

A single quadrant envelope (Fig. 32) was constructed for both polarizations of the five antenna elements in the study. These ten envelope patterns were normalized to unity at the horizon and digitized at five degree intervals for use in the model. Tables 48 through 51 show the data points for both polarizations of each element.

The digitized patterns as they were used in the model are plotted in Figures 33-35. Some of the patterns will be noted to have values greater than unity at certain angles. This indicates that, when mounted singly, some elements emit more radiation at these angles than in the main beam or horizontal direction. When the elements are mounted in arrays, this effect is usually obscured by the array factor.

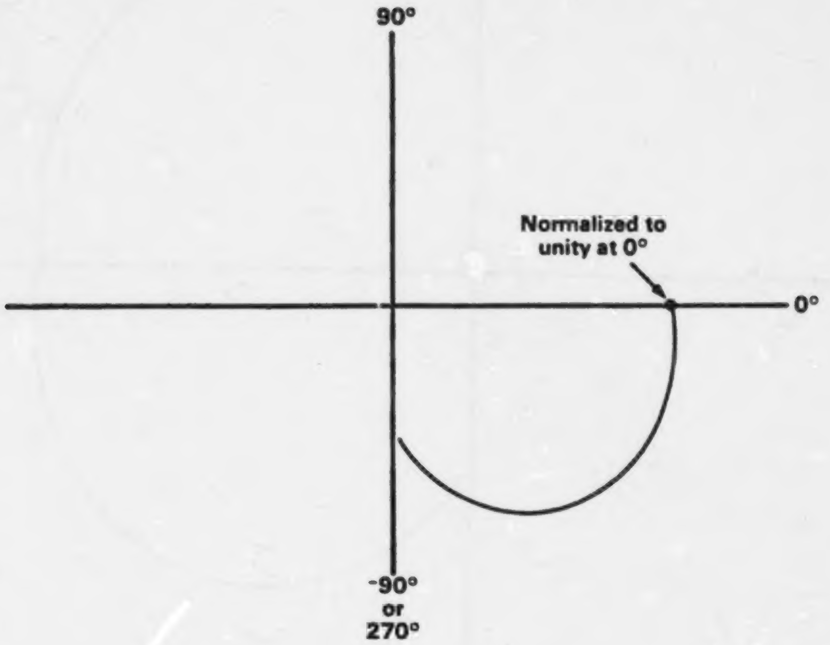

90°
Normalized to unity at 0°
0°
-90° or 270°

Figure 32. Final envelope for one polarization of a single element.

TABLE 48. DATA POINTS FOR TYPE 1 ELEMENT MODEL

Angle (Degrees Below Horizon)	Vertical Polarization (Relative Field Strength)	Horizontal Polarization (Relative Field Strength
0	1.00	1.00
-5	1.00	0.98
-10	1.00	0.95
-15	1.02	0.85
-20	1.12	0.79
-25	1.20	0.76
-30	1.23	0.65
-35	1.23	0.62
-40	1.02	0.55
-45	1.12	0.47
-50	1.15	0.42
-55	1.18	0.39
-60	1.12	0.37
-65	1.12	0.33
-70	1.05	0.30
-75	1.02	0.27
-80	0.98	0.24
-85	0.85	0.21
-90	0.81	0.19

TABLE 49. DATA POINTS FOR TYPE 2 ELEMENT MODEL

Angle (Degrees Below Horizon)	Vertical Polarization (Relative Field Strength)	Horizontal Polarization (Relative Field Strength)
0	1.00	1.00
-5	0.98	1.10
-10	0.85	1.12
-15	0.81	1.23
-20	0.78	1.23
-25	0.65	1.20
-30	0.55	1.12
-35	0.49	1.00
-40	0.44	0.87
-45	0.42	0.68
-50	0.38	0.50
-55	0.35	0.40
-60	0.32	0.28
-65	0.28	0.20
-70	0.25	0.11
-75	0.21	0.06
-80	0.17	0.03
-85	0.13	0.02
-90	0.11	0.03

TABLE 50. DATA POINTS FOR TYPE 3 ELEMENT MODEL

Angle (Degrees Below Horizon)	Vertical Polarization (Relative Field Strength)	Horizontal Polarization (Relative Field Strength)
0	1.00	1.00
-5	1.05	1.00
-10	1.02	0.93
-15	0.98	0.89
-20	0.91	0.81
-25	0.89	0.71
-30	0.72	0.65
-35	0.60	0.63
-40	0.48	0.56
-45	0.39	0.50
-50	0.34	0.40
-55	0.28	0.32
-60	0.21	0.23
-65	0.16	0.16
-70	0.11	0.12
-75	0.07	0.09
-80	0.05	0.05
-85	0.03	0.03
-90	0.03	0.03

TABLE 51. DATA POINTS FOR TYPE 4 ELEMENT MODEL

Angle (Degrees Below Horizon)	Vertical Polarization (Relative Field Strength)	Horizontal Polarization (Relative Field Strength)
0	1.00	1.00
-5	0.98	0.91
-10	0.95	0.93
-15	0.91	0.91
-20	0.89	0.91
-25	0.89	0.93
-30	0.89	0.91
-35	0.81	0.83
-40	0.74	0.66
-45	0.63	0.51
-50	0.51	0.42
-55	0.41	0.39
-60	0.33	0.32
-65	0.25	0.28
-70	0.19	0.19
-75	0.14	0.14
-80	0.10	0.10
-85	0.08	0.06
-90	0.07	0.06

TABLE 52. DATA POINTS FOR TYPE 5 ELEMENT MODEL

Angle (Degrees Below Horizon)	Vertical Polarization (Relative Field Strength)	Horizontal Polarization (Relative Field Strength)
0	1.00	1.00
-5	1.00	0.91
-10	0.89	0.87
-15	0.81	0.83
-20	0.63	0.81
-25	0.60	0.76
-30	0.52	0.74
-35	0.51	0.79
-40	0.46	0.74
-45	0.41	0.58
-50	0.33	0.39
-55	0.29	0.30
-60	0.22	0.28
-65	0.16	0.26
-70	0.14	0.23
-75	0.13	0.19
-80	0.11	0.14
-85	0.10	0.09
-90	0.09	0.07

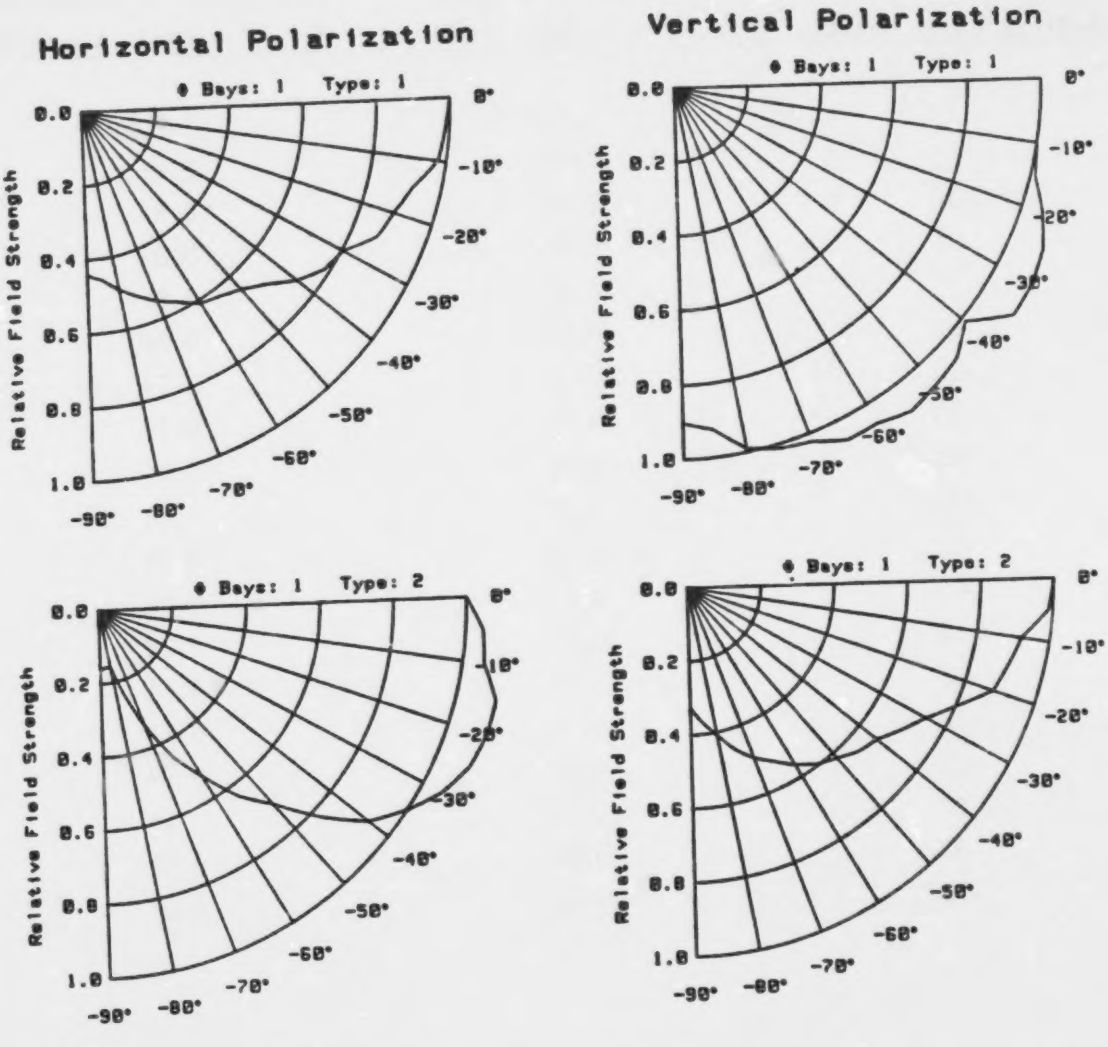


Figure 33. Elevation patterns for Type 1 and Type 2 elements.

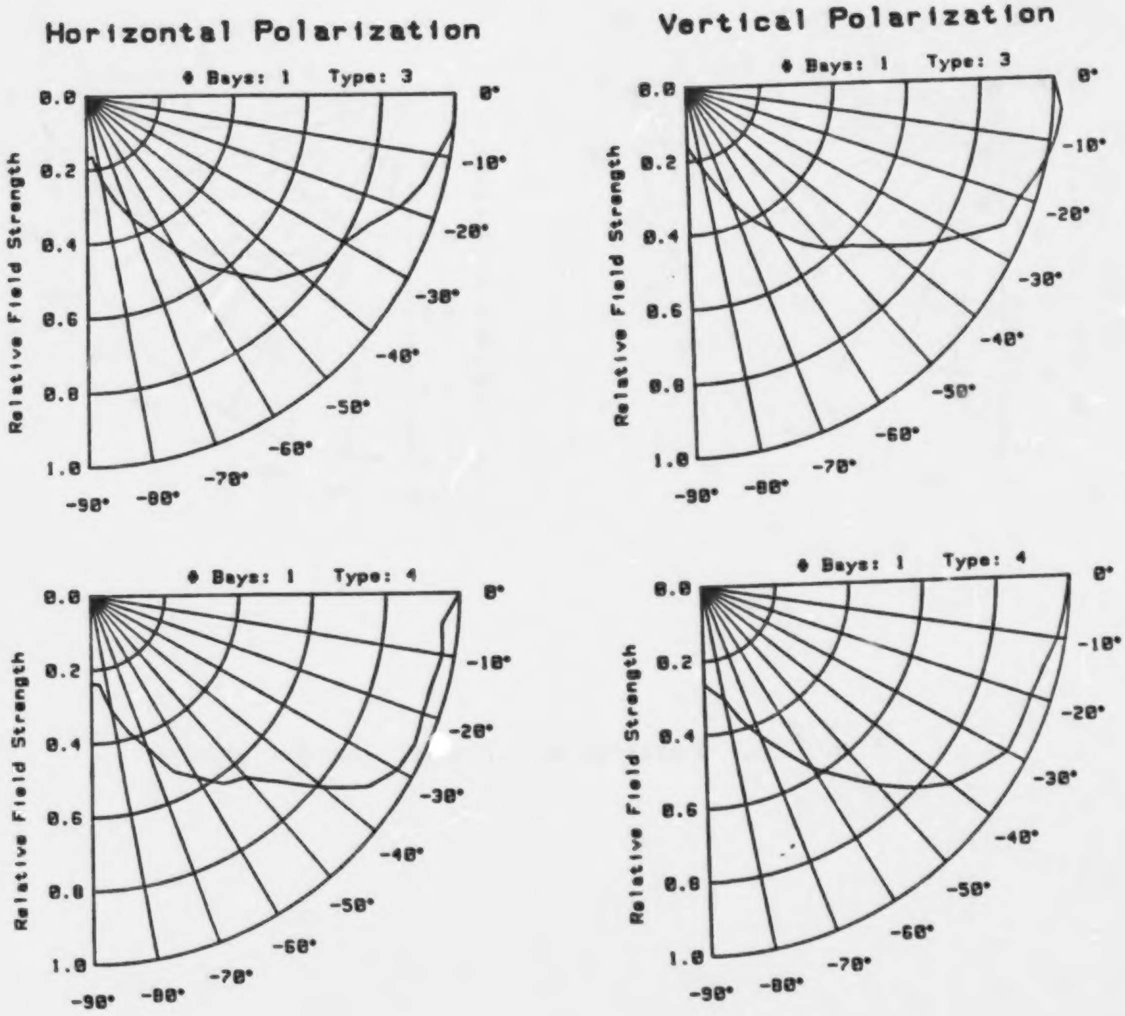


Figure 34. Elevation patterns for Type 3 and Type 4 elements.

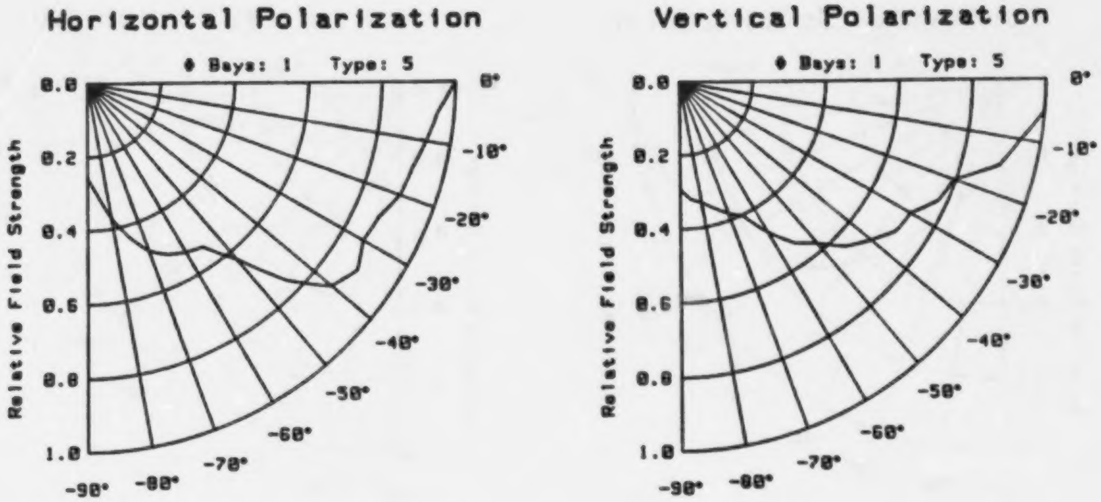


Figure 35. Elevation patterns for Type 5 elements.

Section 3. Arrays and Pattern Multiplication

FM broadcast antennas normally consist of arrays of up to 16 elements stacked vertically on a tower. The elements are spaced approximately one wavelength apart and are usually fed in phase with equal power division between the elements. The relative field strength pattern of these antennas is the product of the element and array patterns. Far-field array patterns for in phase point sources can be generated in a number of ways. The simple formula below is one method.

$$\frac{E_A}{E_D} = \frac{\mathrm{Sin}\ n\ \psi/2}{\mathrm{Sin}\ \psi/2}$$

where E_A = Electric field strength from the array

E_D = Electric field strength which would result from a single element radiating the same total power as the array

$\psi = 2\pi d/\lambda \cos \phi$

d = separation between elements

λ = wavelength

ϕ = angle of measurement direction with respect to the horizontal

n = the number of elements

Polar plots of $E_A/(n * E_D)$ are shown in Figure 36 for n = 2, 4, 6, and 12 with d = one wavelength. The plots are normalized at 0° and do not illustrate the increase in gain as n is increased. They do show that the beam narrows at higher values of n. The total patterns (element times array) for the five elements used in this study grouped in six bay arrays are shown in Figures 37-39.

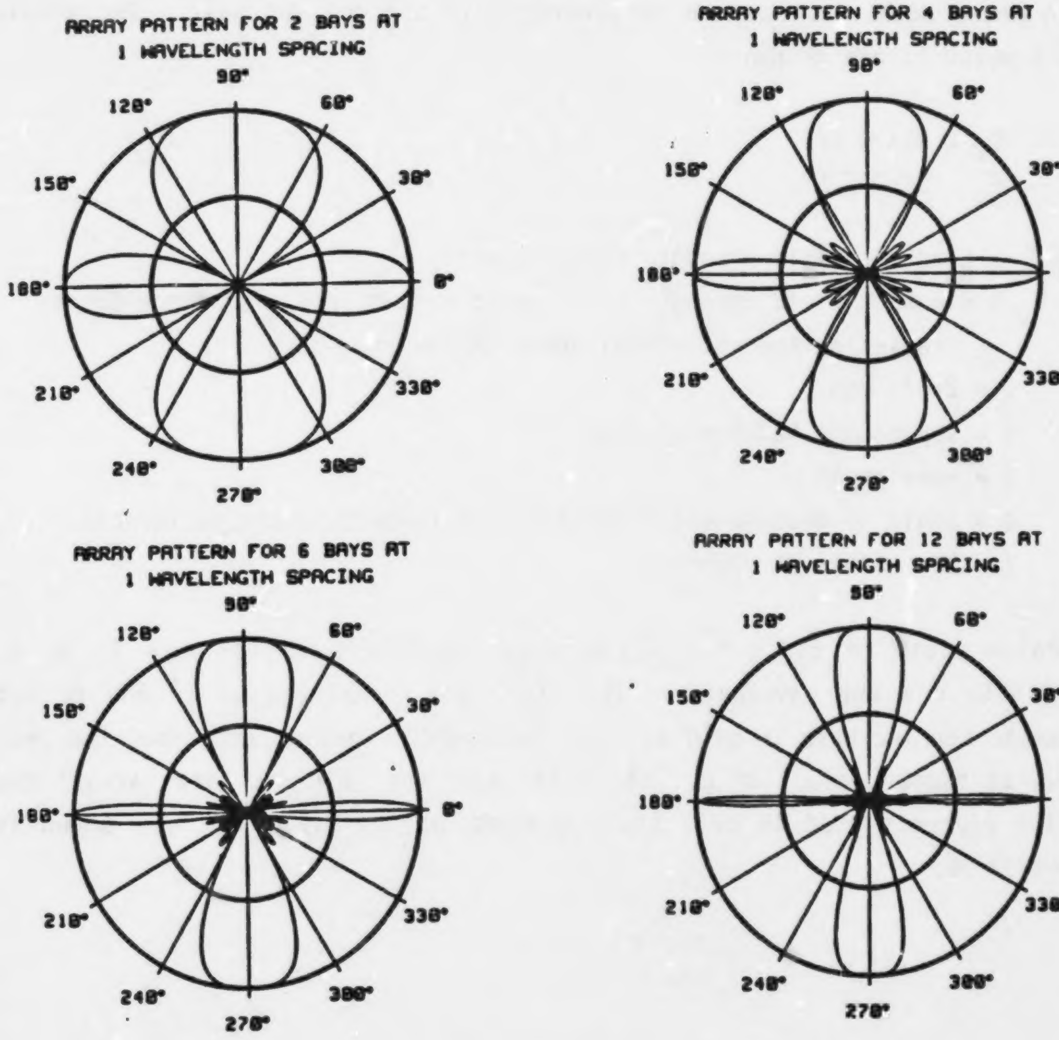


Figure 36. Array patterns for 2, 4, 6, and 12 bays.

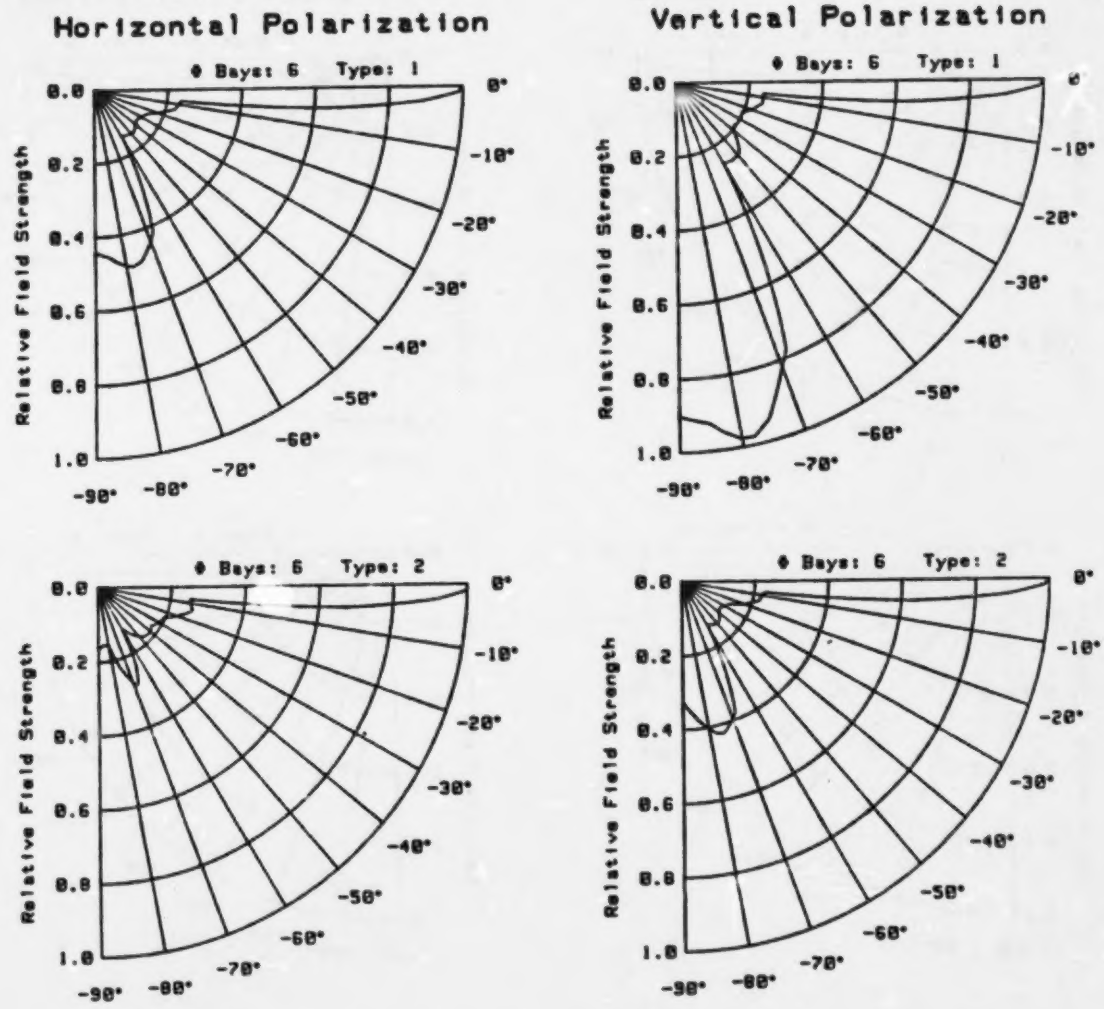


Figure 37. Total patterns for Type 1 and Type 2 elements.

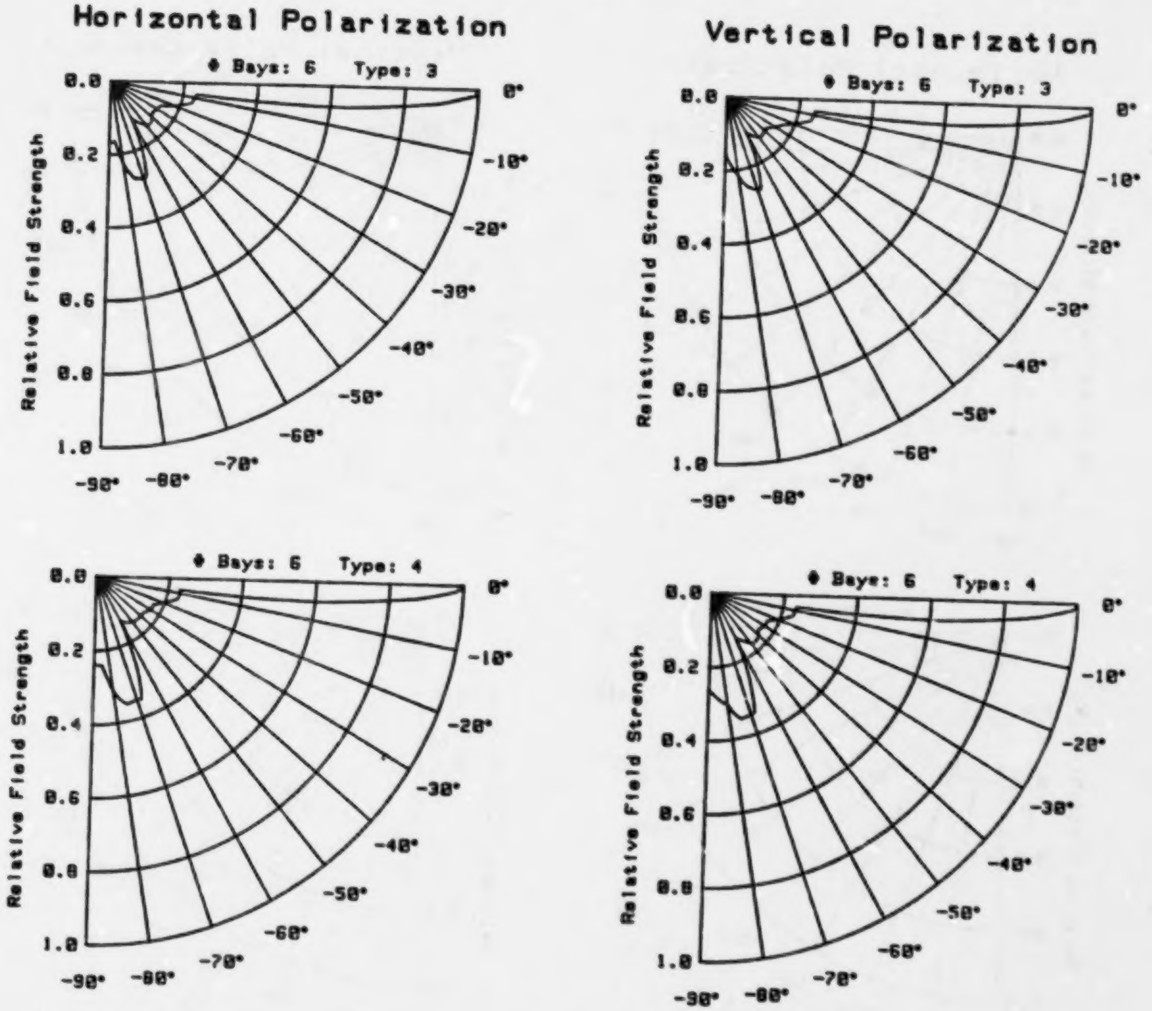
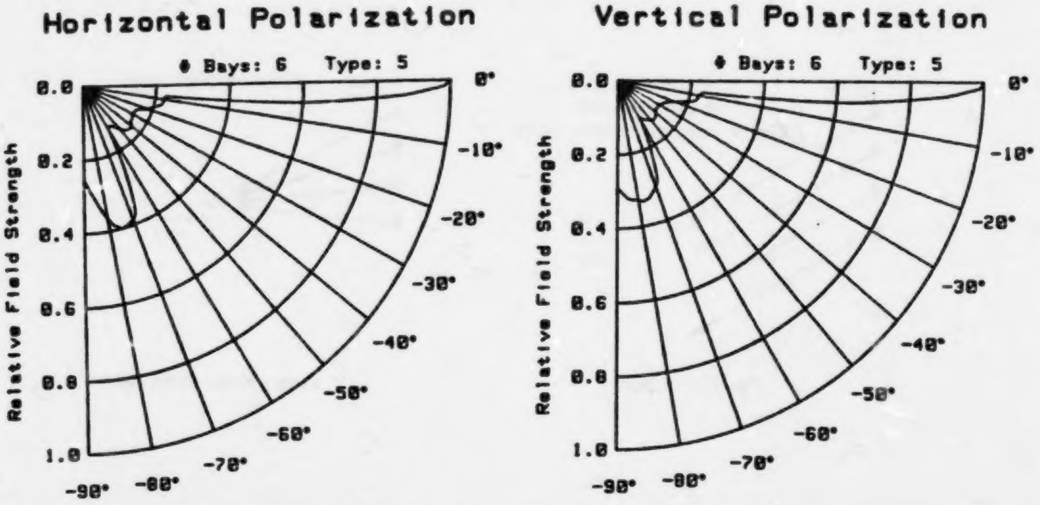


Figure 38. Total patterns for Type 3 and Type 4 elements.



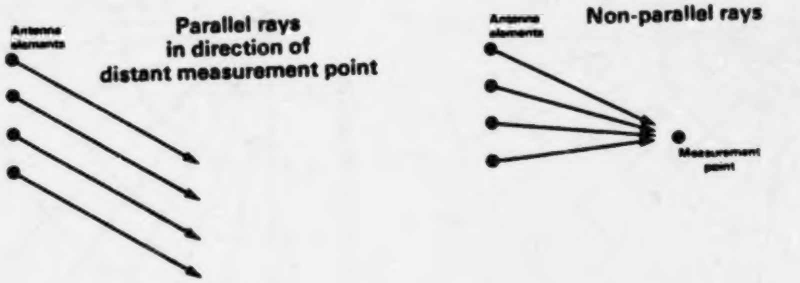
Horizontal Polarization

Vertical Polarization

Figure 39. Total patterns for Type 5 elements.

Section 4 - Array Near-field Effects

The array patterns discussed in Section 3 are far-field patterns which means that the rays from each element are practically parallel at the measurement point. Close to the array, the rays can no longer be considered parallel as illustrated in Figure 40.



Far-field Case

Array Near-field Case

Figure 40. Rays from each element are nearly parallel for points in the far-field but not for points in the array near-field.

The region near the antenna where this effect is significant can be termed the array near-field. It differs from the element near-field which extends only a few feet from each element. The array near-field region for FM broadcast can extend several hundred meters from the antenna. In this region, the far-field pattern does not accurately represent the radiation occurring around the antenna.

Array near-field effects must be considered in impact modeling since they occur in the region near the antenna where the Guidance is most likely to be exceeded. The array near-field region can be examined by calculating the phase and magnitude of the electric fields produced by each element and adding them vectorially. Calculation of the field produced by a two-bay array is shown in Figure 41.

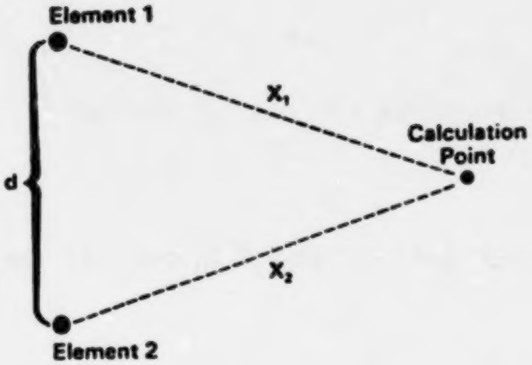


Figure 41. Calculation of the field produced by a two-bay array.

θ = Phase difference = $(X_1 - X_2) * 2\pi/\lambda$
d = separation between elements
λ = wavelength
E_1 = rms electric field produced by element 1
E_2 = rms electric field produced by element 2

$$E_1 = \sqrt{\frac{377 * P_1}{4 * \pi * X_1^2}}$$

$$E_2 = \sqrt{\frac{377 * P_2}{4 * \pi * X_2^2}}$$

P_1 = power radiated by element 1
P_2 = power radiated by element 2
E_R = rms resultant electric field (superposition of E_1 and E_2 at the measurement point)

$$E_R = \sqrt{E_1^2 + E_2^2 + 2E_1E_2 \text{ Cos } \theta}$$

A more general method for combining waves from arrays with any number of elements was developed for this study. Assuming that N sinusoidally varying waves of the same frequency ($\omega/2\pi$) but different peak amplitudes (E_n) and phases (θ_n) combine, the principle of superposition states that the resultant wave will be specified by:

$$E(t) = \sum_{n=1}^{N} E_n \sin(\omega t + \theta_n)$$

Using $\sin(x + y) = \sin x \cos y + \cos(y) \sin(y)$

$$E(t) = \sum_{n=1}^{N} E_n \sin(\omega t) \cos(\theta_n) + E_n \cos(\omega t) \sin(\theta_n)$$

$$= \sin \omega t \sum_{n=1}^{N} E_n \cos(\theta_n) + \cos(\omega t) \sum_{n=1}^{N} E_n \sin(\theta_n)$$

Setting $A = \sum_{n=1}^{N} E_n \cos(\theta_n)$

and

$$B = \sum_{n=1}^{N} E_n \sin(\theta_n)$$

$$E(t) = A \sin(\omega t) + B \cos(\omega t)$$

The instantaneous power is given by

$$P_{inst} = \frac{E^2(t)}{377}$$

and integrating over one cycle

$$P_{avg} = \frac{f}{377} \int_0^{1/f} (A \sin \omega t + B \cos \omega t)^2 \, dt$$

where P_{avg} = the average power

and f = frequency.

The integrand can be expanded and P_{avg} expressed as three integrals.

$$P_{avg} = \frac{f}{377} \int_{0}^{1/f} A^2 \sin^2 (\omega t)\, dt$$

$$+ \quad \frac{f}{377} \int_{0}^{1/f} 2\, AB\, \mathrm{Sin}\, (\omega t) \cos (\omega t)\, dt$$

$$+ \quad \frac{f}{377} \int_{0}^{1/f} B^2 \mathrm{Cos}^2 (\omega t)\, dt$$

The second integral equals zero and the first and last simplify to:

$$P_{avg} = \frac{A^2 + B^2}{2 * 377}$$

The magnitude of the peak or rms resultant electric field can then be found

$$E_{R\text{-}peak} = \sqrt{A^2 + B^2}$$

$$E_{R\text{-}rms} = \sqrt{\frac{A^2 + B^2}{2}}$$

The resultant wave is

$$E(t) = E_R \sin (\omega t + \theta_R)$$

where θ_R is the resultant phase angle.

The phase angle θ_R can be found by noting that $E(t) = 0$ when $t = -\theta_R/\omega$. The earlier expression for E(t),

$$E(t) = A \sin (\omega t) + B \cos (\omega t)$$

is set to zero at $t = -\theta_R/\omega$.

$$A \sin(-\theta_R) + B \cos(-\theta_R) = 0$$

$$-A \sin(\theta_R) = -B \cos \theta_R$$

$$\tan(\theta_R) = B/A$$

$$\theta_R = \tan^{-1}(B/A)$$

Thus, the resulting wave is completely identified assuming that all component waves are of the same polarization.

The above technique was used to study the importance of array nearfield effects in modeling. A computer program was written which calculated field levels near the ground using far-field (parallel-ray) calculations and array near-field (non-parallel ray) calculations. Results from both techniques were plotted on the same graph for comparison. Figures 42-44 are examples of the output of this program. The value for height above ground in these graphs is the height of the lowest element. The program does not consider coupling between elements or ground reflections.

Examination of Figures 42 through 44 reveals two differences between the results of the two calculational methods. Nulls in the array near-field plots tend to be shallower and shifted in position when compared to the far-field plots. These effects are most prominent when the array is mounted on a low tower (Figure 42). For high towers, as in Figure 43, the far-field plot is a good approximation of the near-field plot.

The implication of these results is that array pattern nulls should be ignored in impact modeling. Further support for this concept is that many stations deliberately fill the nulls through phasing techniques to improve coverage. To avoid under-predicting the fields at null locations, the FM model uses far-field array patterns with 100 per cent null fill. These patterns are constructed by drawing an envelope around far-field patterns. Figure 45 shows a far-field array pattern and the constructed envelope. Envelopes of 1,2, 3, 4, 5, 6, 7, 8, 10, 12, 14, and 16 bay far-field array patterns were digitized and stored in files for use in the FM model.

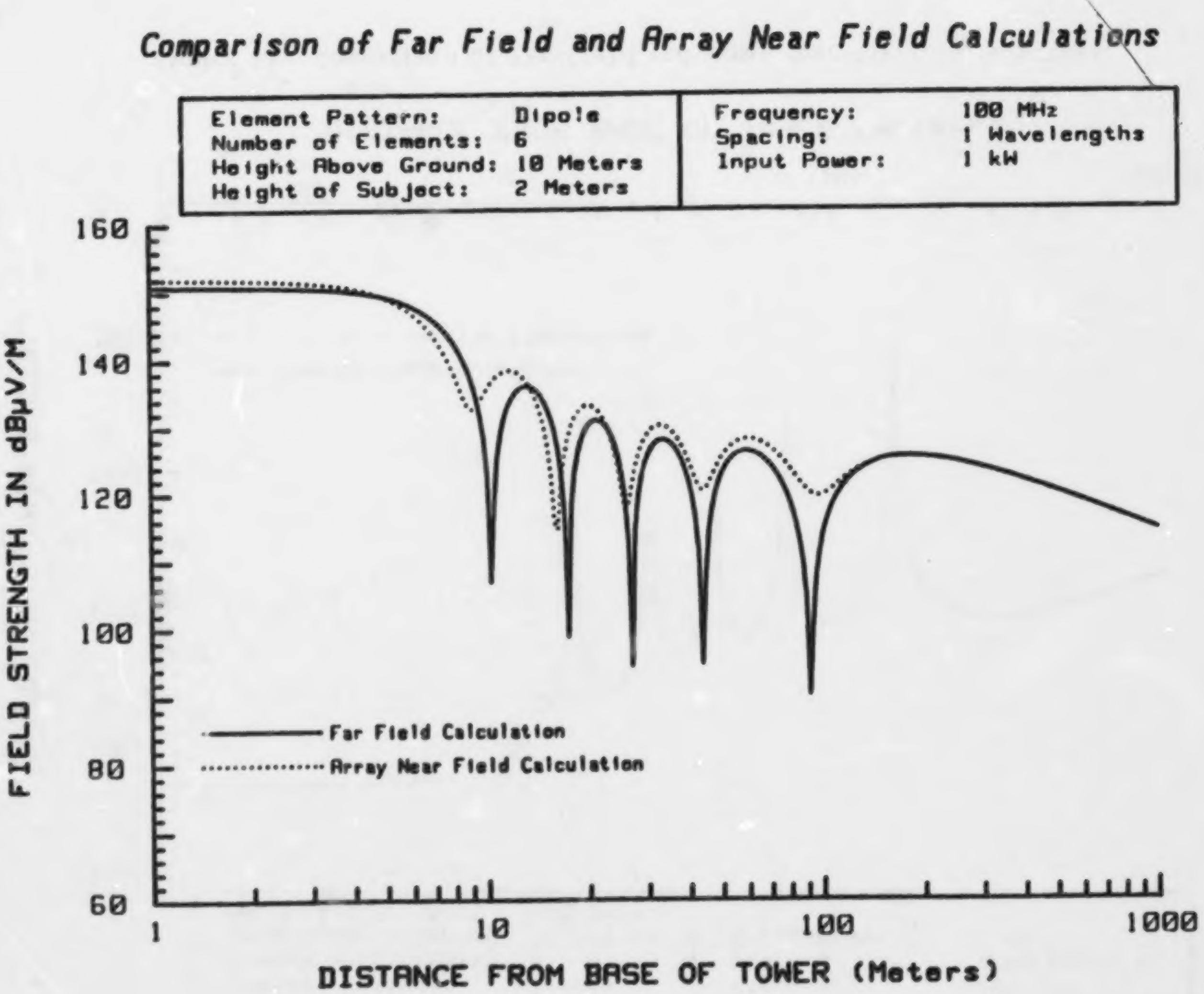


Figure 42. Comparison of far-field and array near-field calculations.

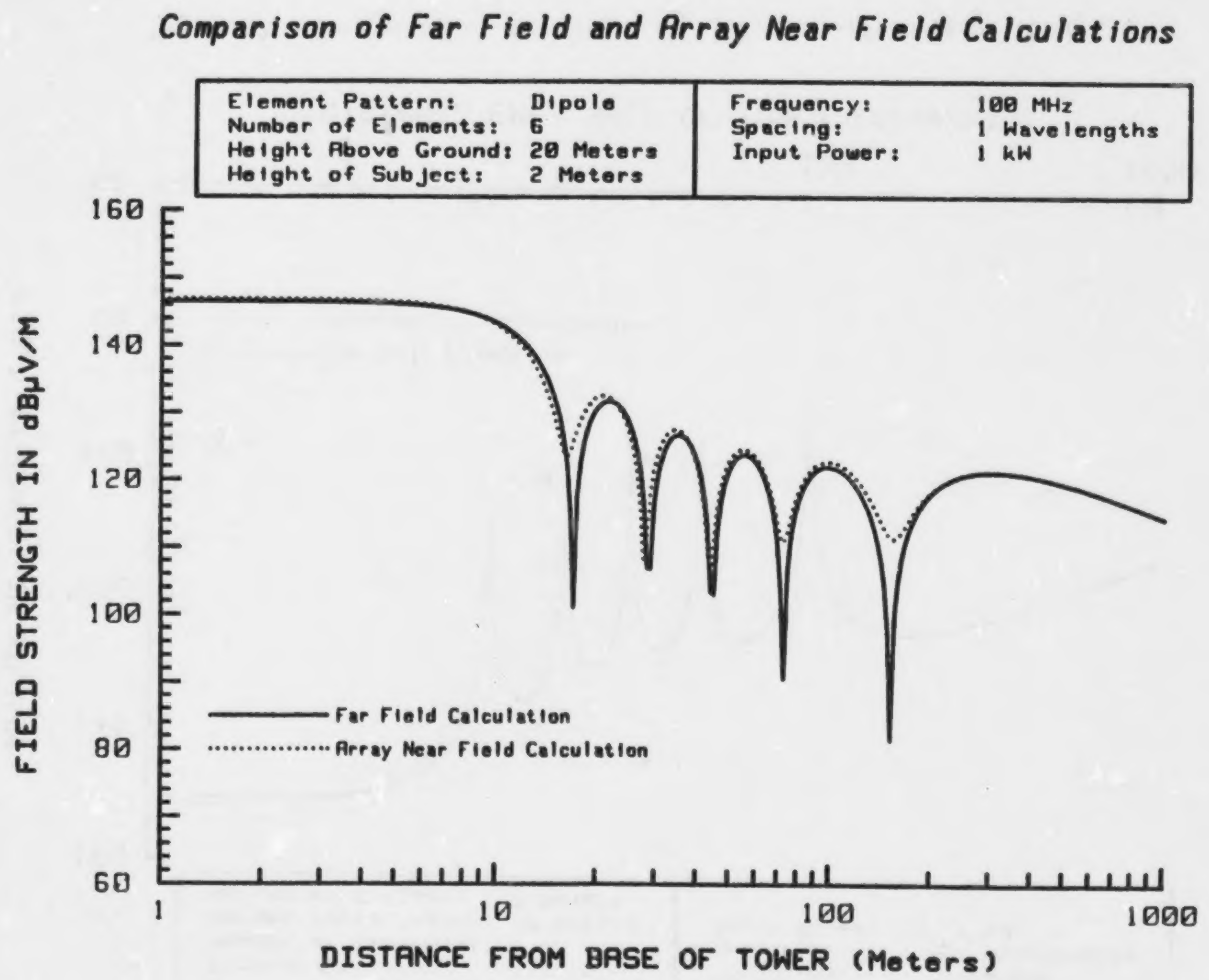


Figure 43. Comparison of far-field and array near-field calculations.

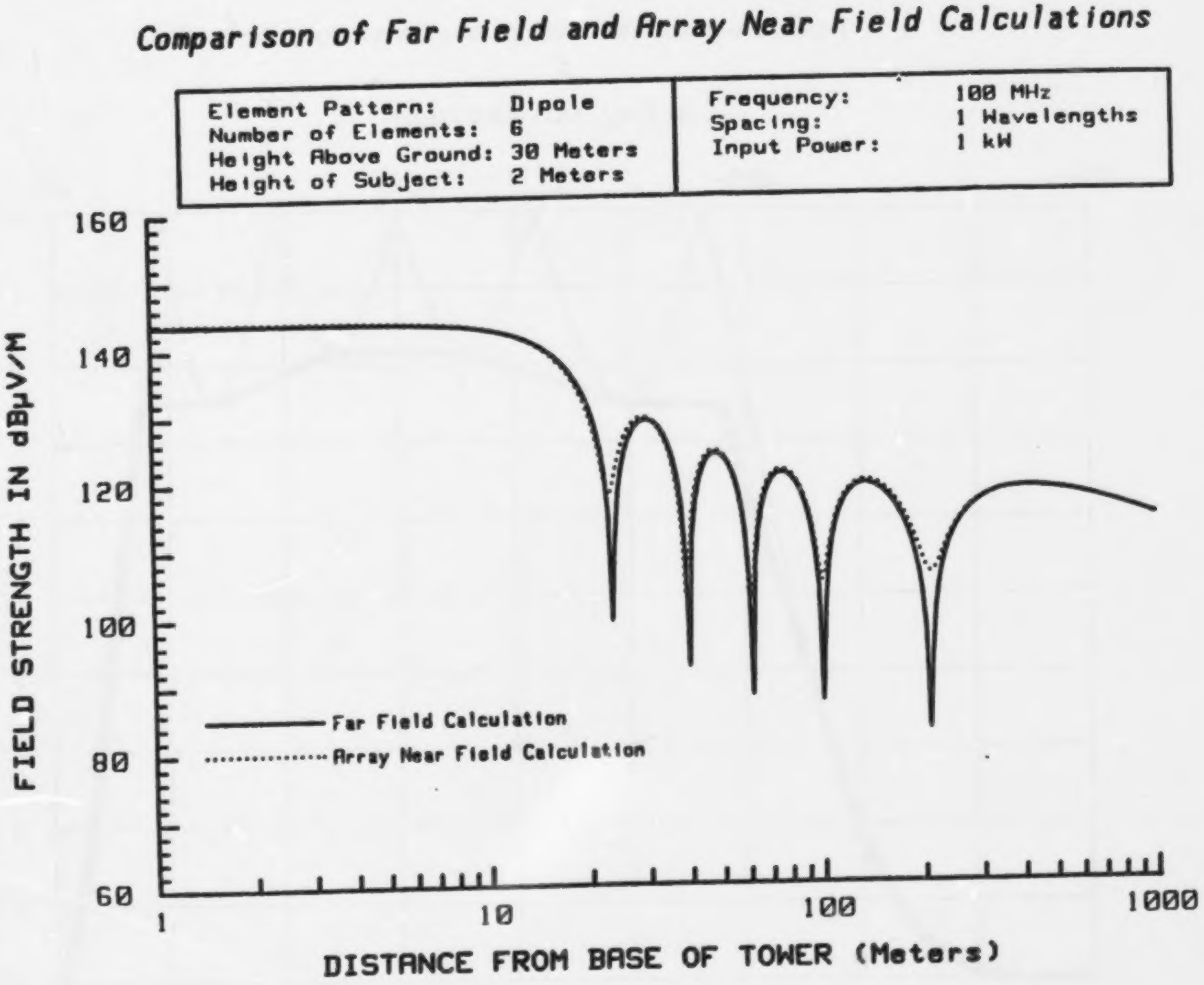


Figure 44. Comparison of far-field and array near-field calculations.

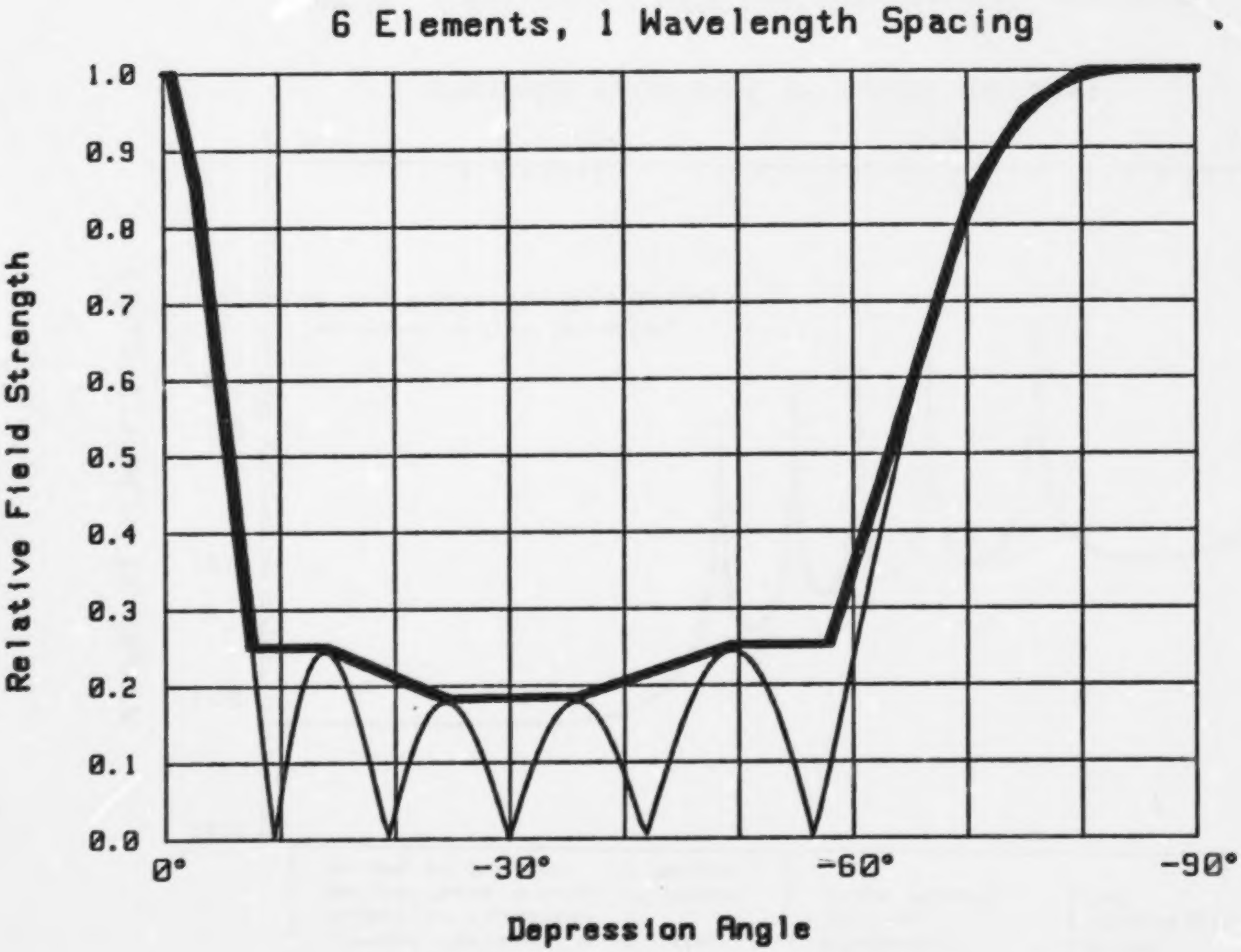


Figure 45. Construction of an array envelope model.

Section 5 - Mutual Coupling Effects

The technique of pattern multiplication described in Section 3, Appendix A, ignores mutual coupling effects which can be important in certain antenna configurations. Each element of an array interacts with other nearby elements changing its net impedance. The net impedance for the first element in an N-bay array, for example, is:

$$Z_{1(net)} = Z_{1(self)} + \sum_{n=2}^{N} Z_{1,n}$$

where $Z_{1(net)}$ = the net impedance of the first element
Z_{self} = the self impedance of the first element
$Z_{1,n}$ = the mutual impedance between elements 1 and n

For a given input power, changes in impedance change the current in the element and consequently the radiated field. As an example, the electric field at a point produced by a one-half wave dipole can be expressed as:

$$E_D = kI_D$$

where E_D = the electric field produced by the dipole at a given point
I_D = the current in the dipole
k = a constant involving the distance between the dipole and measurement point

If the same element is placed in an array:

$$E_E = k\, I_E$$

Assuming that power is held constant

$$I_D^2 R_D = I_E^2 R_E$$

where R denotes the real part of the antenna's impedance

Rearranging terms,

$$\frac{I_D}{I_E} = \sqrt{\frac{R_E}{R_D}}$$

or

$$\frac{E_D}{E_E} = \sqrt{\frac{R_E}{R_D}}$$

and

$$E_E = E_D \sqrt{\frac{R_D}{R_E}}$$

Thus, when an element is placed in an array, the resulting electric field changes by the square root of the ratio of resistances,

$$\sqrt{\frac{R_D}{R_E}}$$

Exact calculations of mutual impedances have been worked out only for simple geometries such as broadside or colinear dipole antennas. Actual FM broadcast antennas are far from dipoles in shape and radiation patterns making theoretical impedance calculations impractical. In order to get some idea of mutual coupling effects, broadside arrays of one-half wave dipole elements were modeled using equations from Kraus [4]. Results of the modeling showed that coupling effects can significantly alter the predicted field levels for certain interbay spacings, but are minimal when the spacings are near one wavelength.

The above results are not directly applicable to actual FM broadcast antennas for two reasons. First, the broadcast elements have a substantial vertical height such that not all points on the element are the same distance from adjacent elements. Second, broadcast arrays typically use spacings slightly less than one wavelength. Coupling is reduced, however, by the fact that broadcast elements radiate less energy up and down (towards the other elements) than dipoles. Without a very extensive numerical analysis and knowledge of the feed systems used, it is impossible to predict the exact effects of mutual coupling. As a first approximation, the above factors indicate that coupling effects in FM antennas can be ignored without seriously affecting the accuracy of the model.

Section 6 - Effect of Ground Reflections

Electromagnetic waves striking the ground from an FM broadcast antenna are reflected and add to or subtract from direct waves to alter the total field (See Figure 46).

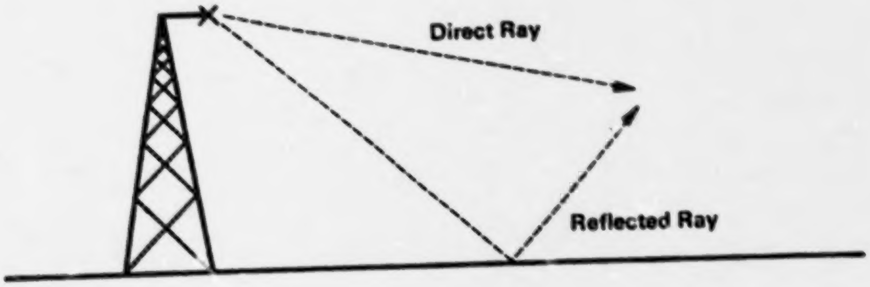


Figure 46. Field strength at a point is the result of the direct and reflected wave.

Consideration of ground reflections is important in impact modeling since field strengths can be significantly increased. Field enhancement by reflected waves can result in increases in field strength which may not, in some circumstances, correspond to a similar increase in power density. The worst case increase from a reflection as shown in Figure 46 would be a doubling of field strength. For free space waves, a doubling in field strength corresponds to a quadrupling in power density. Reflections, however, create standing waves. In a standing wave the power density could be zero if, for example, the magnetic field is zero but the electric field is large. Nevertheless, field enchancement due to reflection must be considered in impact modeling because proposed Federal Guidance would most likely be stated in terms of electric field, magnetic field, and power density. Any of these three quantities can be the limiting parameter in a given situation. Where wavelengths are less than the height of the subject, calculation or measurement of either electric or magnetic field is satisfactory. In these cases, the value of either field maxima will correspond to the free space equivalent (E = 377H) of the other field maxima which will also occur near the ground.

The actual position and intensity of the field maximas depends on the factors listed below:

1. polarization of the signal
2. frequency of the signal (f)
3. ground conductivity (σ)
4. ground dielectric constant (ϵ)
5. angle that wave makes with the earth (ψ) (see Figure 47)
6. roughness of terrain

Equations for calculating the magnitude and phase of the reflected signal are given in Jordan and Balmain [3].

$$R_v = \frac{(\epsilon_r - jX)\sin(\psi) - \sqrt{(\epsilon_r - jX) - \cos^2(\psi)}}{(\epsilon_r - jX)\sin(\psi) + \sqrt{(\epsilon_r - jX) - \cos^2(\psi)}}$$

$$R_h = \frac{\text{Sin}(\psi) - \sqrt{(\epsilon_r - jX) - \cos^2(\psi)}}{\text{Sin}(\psi) + \sqrt{(\epsilon_r - jX) - \cos^2(\psi)}}$$

These equations express the reflection coefficients for vertically and horizontally polarized signals as complex numbers. After extensive manipulation, they can be expressed as a real and imaginary part and then used to calculate the magnitude and phase of the reflected signal. Techniques of vector addition such as those described in Section 4, Appendix A, can be used to sum the direct and reflected rays at a given point to determine the resultant field. The final form of the equations for R_h and R_v are given below using intermediate variables to reduce the size of the expressions.

$$\text{Set } X = \frac{\sigma \times 1.8 \times 10^{10}}{f}$$

$$F = \sqrt{\frac{((\epsilon_r - \cos^2(\psi))^2 + X^2)^{1/2} + (\epsilon_r - \cos^2(\psi))}{2}}$$

$$G = \sqrt{\frac{((\epsilon_r - \cos^2(\psi))^2 + X^2)^{1/2} - (\epsilon_r - \cos^2(\psi))}{2}}$$

The reflection coefficients can then be expressed as a real and an imaginary part.

$$R_h(\text{real}) = \frac{2(\epsilon_r F - F + X\,G)\sin(\psi) + (\epsilon_r - 1)\cos 2(\psi) + \epsilon_r - \epsilon_r^2 - X^2}{(1 - \epsilon_r)^2 + X^2}$$

$$R_h\,(\text{imaginary}) = \frac{2(XF + G - G\,\epsilon_r)\sin(\psi) + x\cos 2(\psi) - X}{(1 - \epsilon_r)^2 + X^2}$$

The magnitude of R_h is:

$$\left|R_h\right| = [R_h^2(\text{real}) + R_h^2(\text{imaginary})]^{1/2}$$

and the phase is:

$$R_h\,(\text{phase}) = \text{Atn}\left[\frac{R_h\,(\text{imaginary})}{R_h\,(\text{real})}\right]$$

For vertically polarized signals:

$$R_v(\text{real}) = \frac{(\epsilon_r{}^2 + X^2)\sin^2(\psi) - F^2 - G^2}{(\epsilon_r{}^2 + X^2)\sin^2(\psi) + (2\epsilon_r F + 2GX)\sin(\psi) + F^2 + G^2}$$

$$R_v(\text{imaginary}) = \frac{(2G\epsilon_r - 2XF)\sin(\psi)}{(\epsilon_r^2 + X^2)\sin^2(\psi) + (2\epsilon_r F + 2GX)\sin(\psi) + F^2 + G^2}$$

The magnitude and phase of R_v may be found using expressions similar to those for R_h. Care must be exercised when using the expressions for R_v. Vertical polarization in this context means vertical with respect to an observer at the reflection point looking towards the transmitter.

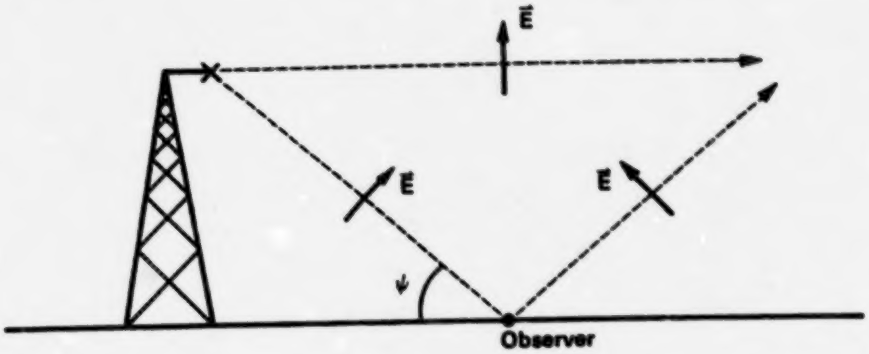


Figure 47. Vertical polarization means that the E-field vector appears vertical to an observer looking towards the source.

Figure 47 illustrates direct and reflected rays emanating from a broadcast antenna. In both cases, the rays are vertically polarized, but one is not perpendicular to the ground. Directly beneath the antenna ($\psi = 90^0$), the electric field of a vertically polarized signal is actually parallel to the ground and equivalent to a horizontally polarized signal.

Plots of the magnitude and phase of the reflection coefficients are shown in Figure 48-51. These were generated using the above equations at 100 MHz, relative dielectric constants of 7-30, and conductivities from 0.001 to 0.03 mho/m. Examination of these curves reveals that directly beneath the antenna, the magnitude of the reflection coefficient ranges from about 0.45 to 0.70 for the range of dielectric constants and conductivities commonly found in the

United States [5]. It was felt that the lack of knowledge concerning terrain, buildings, and electrical properties of the soil around each station precluded the possibility of calculating accurate reflection coefficients at each point. Thus a constant value of 0.6 was chosen as an approximation to the actual reflection coefficients for use in the model. Although the horizontal reflection coefficient increases with distance from the tower a decrease in vertical reflection coefficient also occurs. Thus, multiplying all predicted fields by a constant 1.6 appears to be a reasonable aporoach to modeling field enhancement by ground reflections.

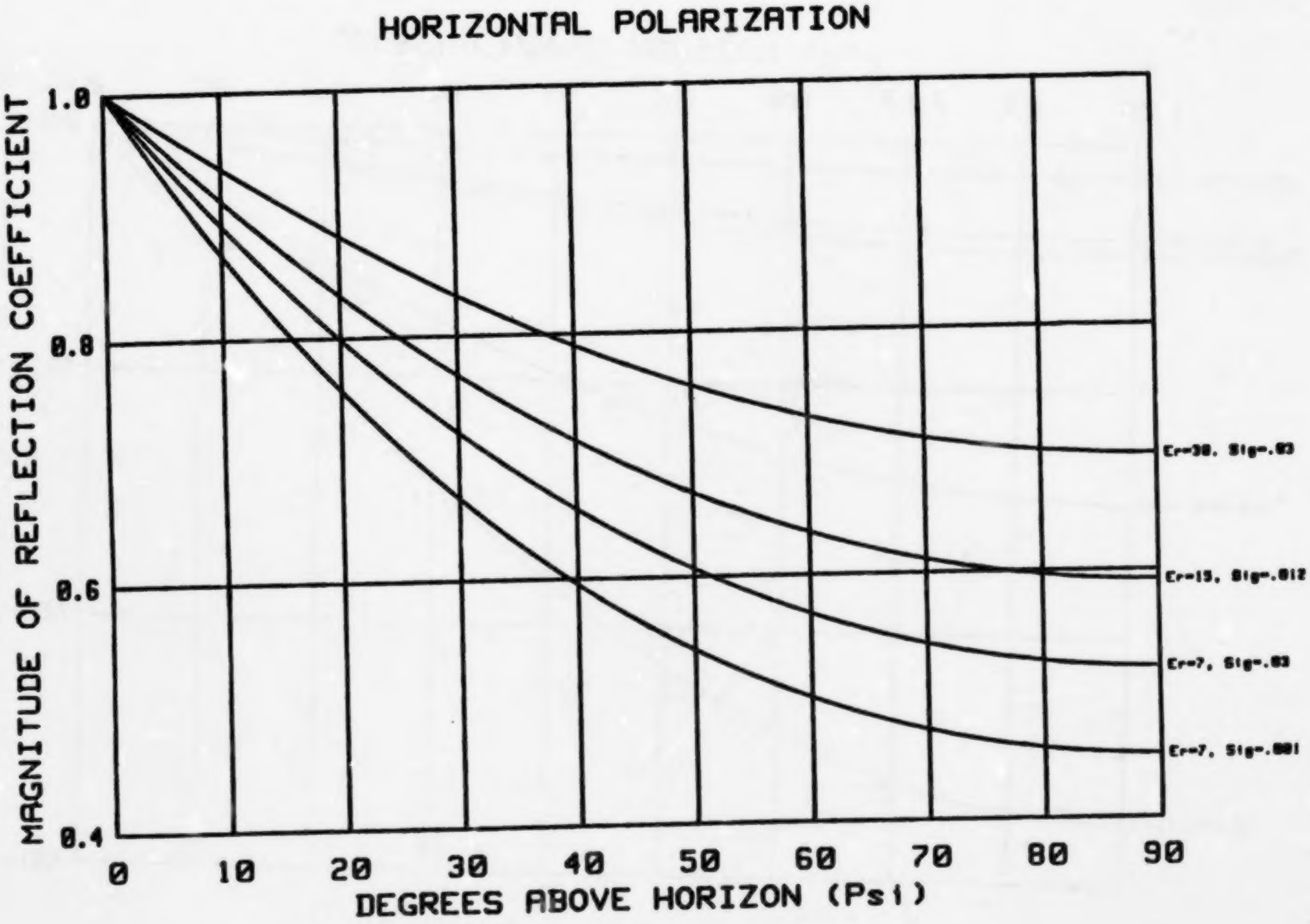


Figure 48. Magnitude of the reflection coefficient for horizontally polarized signals.

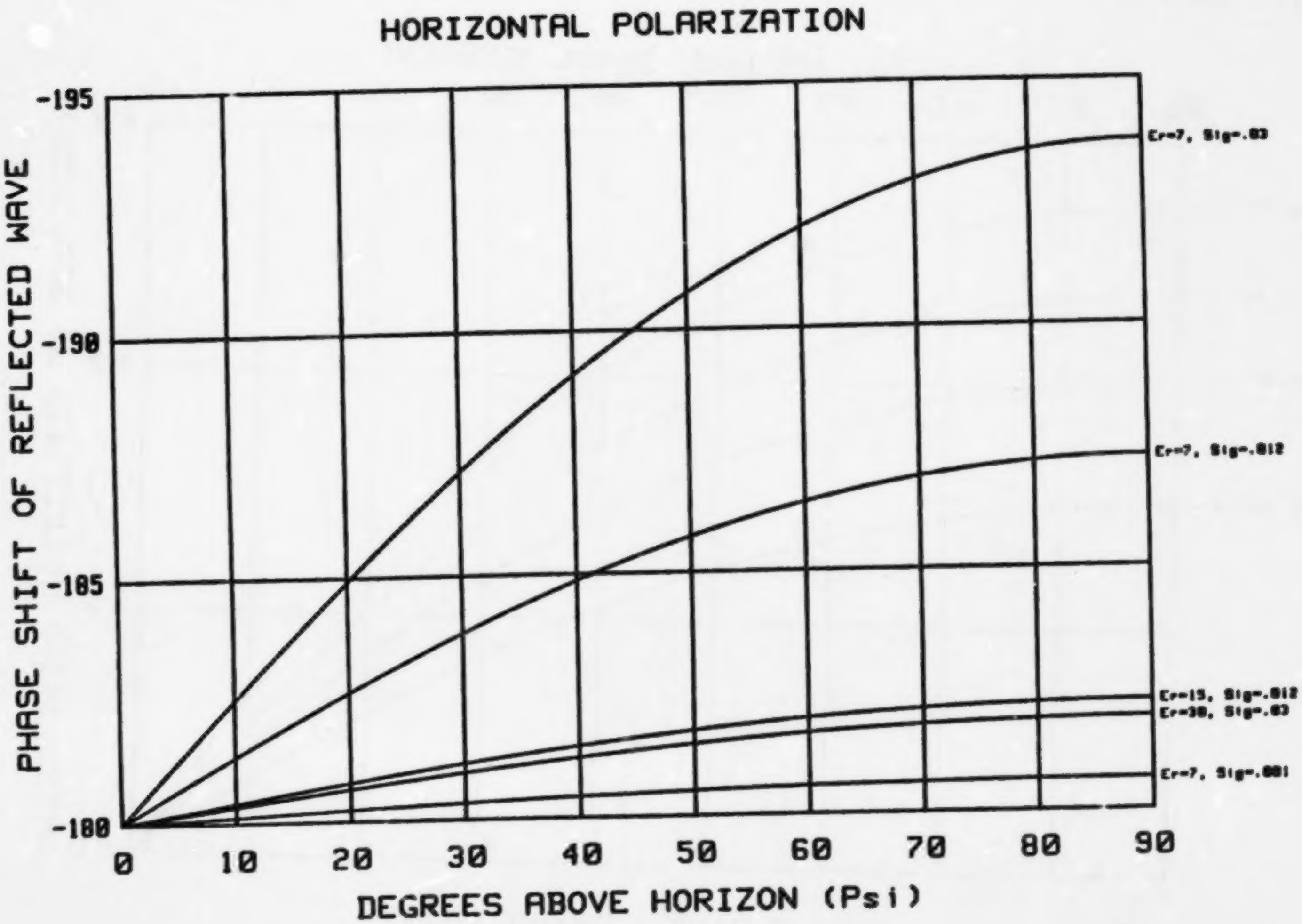


Figure 49. Phase shifts of reflected horizontally polarized signals.

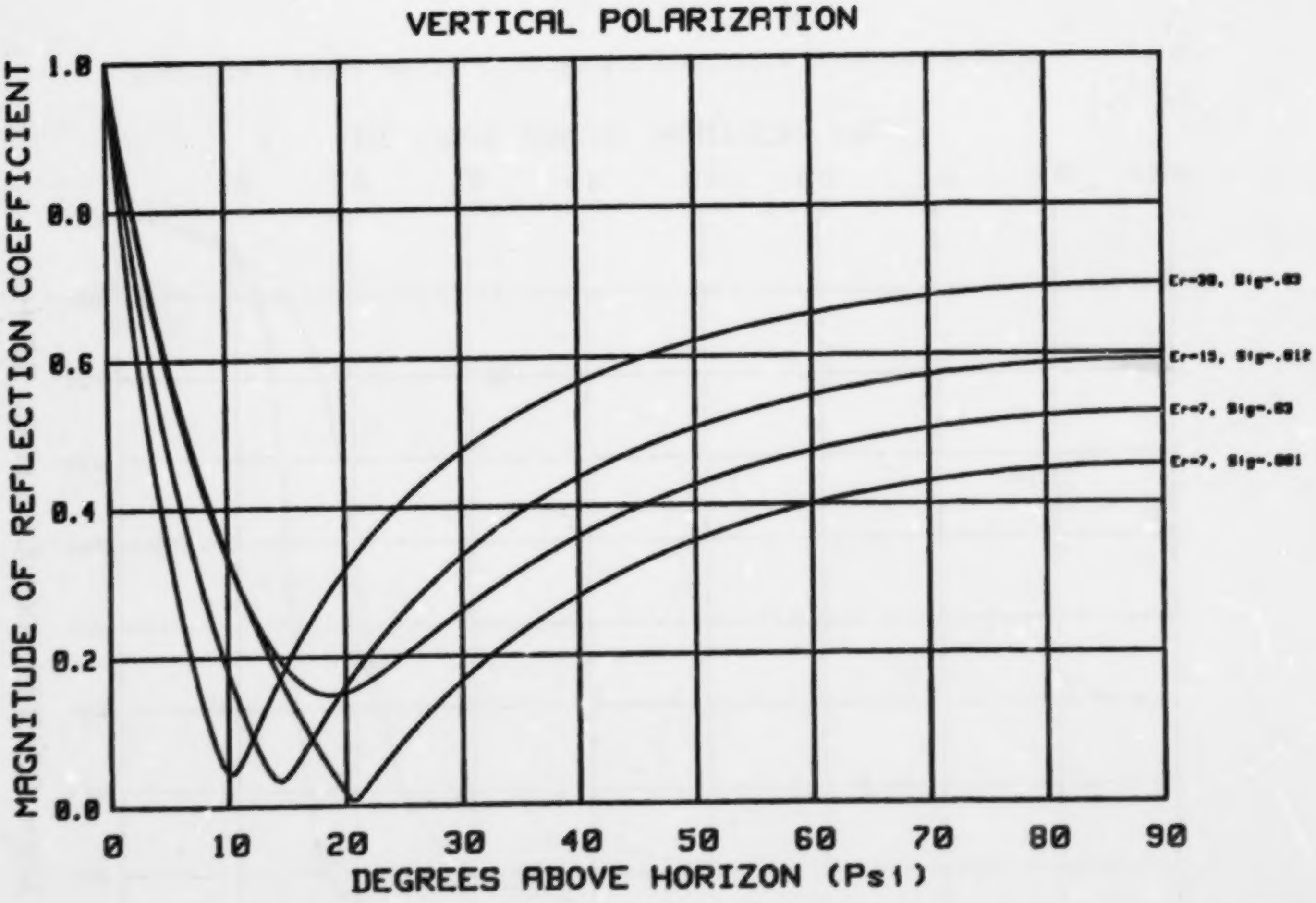


Figure 50. Magnitude of the reflection coefficient for vertically polarized signals.

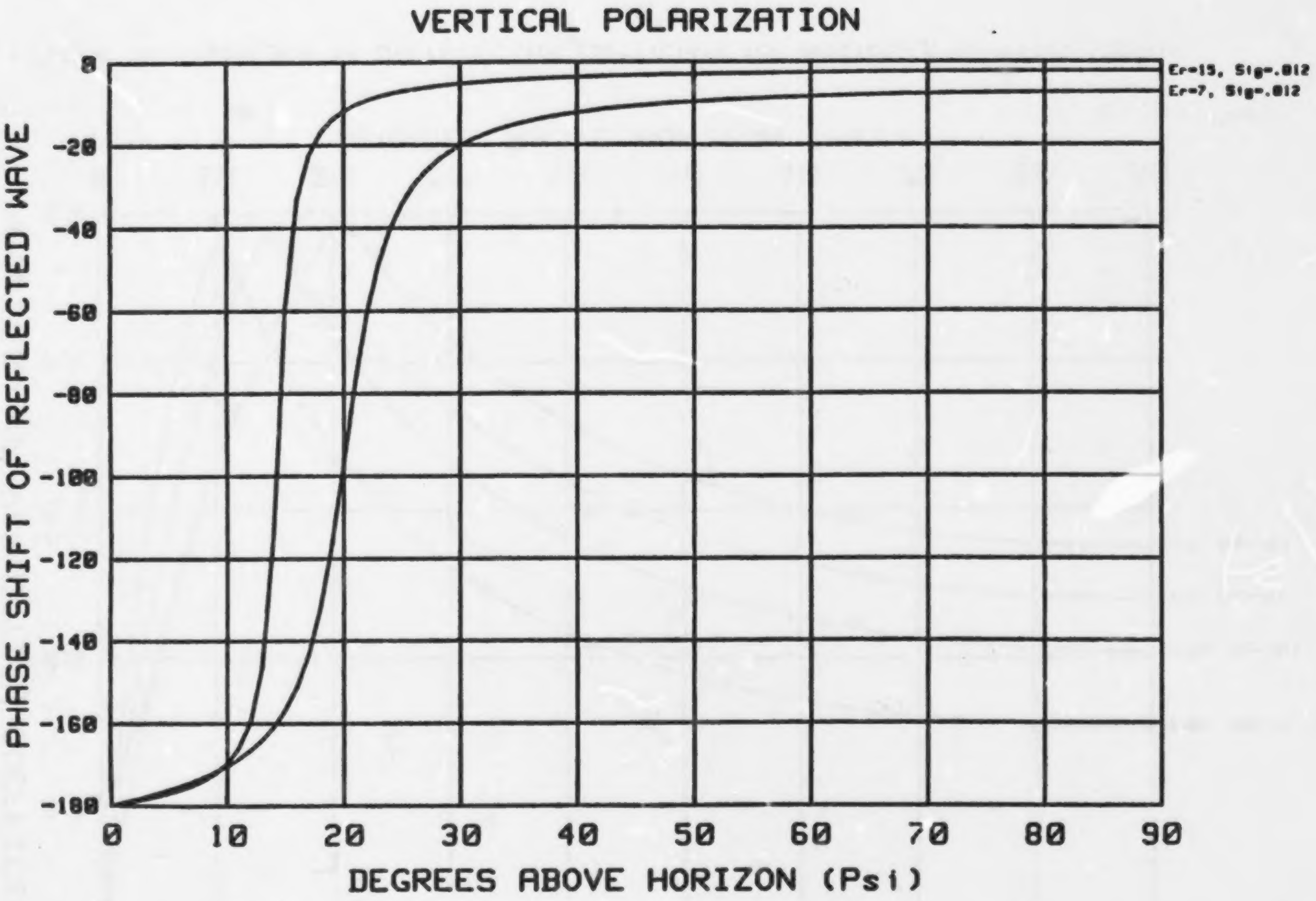


Figure 51. Phase shifts of reflected vertically polarized signals.

Appendix B - FM Model Verification

In order to verify the accuracy of the FM model, a field study was conducted in August 1982. Measurements were made around six FM stations which represented a variety of antenna types, ERP's, and terrains. After the study, the measured field strength values were plotted as free-space equivalent power densities for comparison with the FM model output for those stations.

Holaday Industries Model 3001 electric field strength meters were used to make the measurements. These meters were calibrated beforehand in a transverse electromagnetic cell (TEM) at EPA which has been characterized to better than ± 1 dB accuracy. The meters were found to accurately measure field with errors less than ± 2 dB. As mentioned in Section 6 of Appendix A, measurement of electric field alone is sufficient for FM broadcast stations. The electric field maxima will always occur at heights above ground which can be reached with a hand-held probe (typically less than 3 ft.). These maxima will be similar in intensity to the magnetic field maxima and greater than the true power density if a free-space conversion (based on the square of the field strength and free-space impedance) is used.

Since the FM model predicts the highest equivalent power density expected at each radial distance from the base of the tower, measurements were taken to reflect the same concept. The ideal measurement method would be to choose about eight or more equally spaced radial directions away from the tower and take measurements along each at three foot intervals. At each measurement distance, the probe is raised slowly from the ground to eight feet while watching the meter for a maximum value. Once the location of the maxima is found, the region is carefully probed to determine the maximum reading. Values obtained along the various radials are then compared and the highest value for each distance from the tower is used.

It was not possible to follow the above protocol exactly at most of the measurement sites. Buildings and terrain features often prevented measurement along all radial directions. However, after measuring field strengths in as many locations as possible, it was often found that the highest field strengths occurred along a single radial. In all cases, efforts were made to duplicate the results of the ideal method within the physical constraints of the location.

Figures 52 through 56 show the measured values plotted along with the curve predicted by the EPA FM model for each station in the study. Examination of these graphs show that the predicted curves are in good agreement with the measured values. The intention of the FM model is to predict an envelope or upper bound of the actual values occurring at a station. This goal appears to have been met to a reasonable degree for the six stations measured. In some cases the measured values exceeded the predicted curve at certain points, but in all cases the highest value predicted by the model was not exceeded by the measurements. Since impact predictions were based on the highest values predicted by the model, these results add to the credibility of the impact analysis.

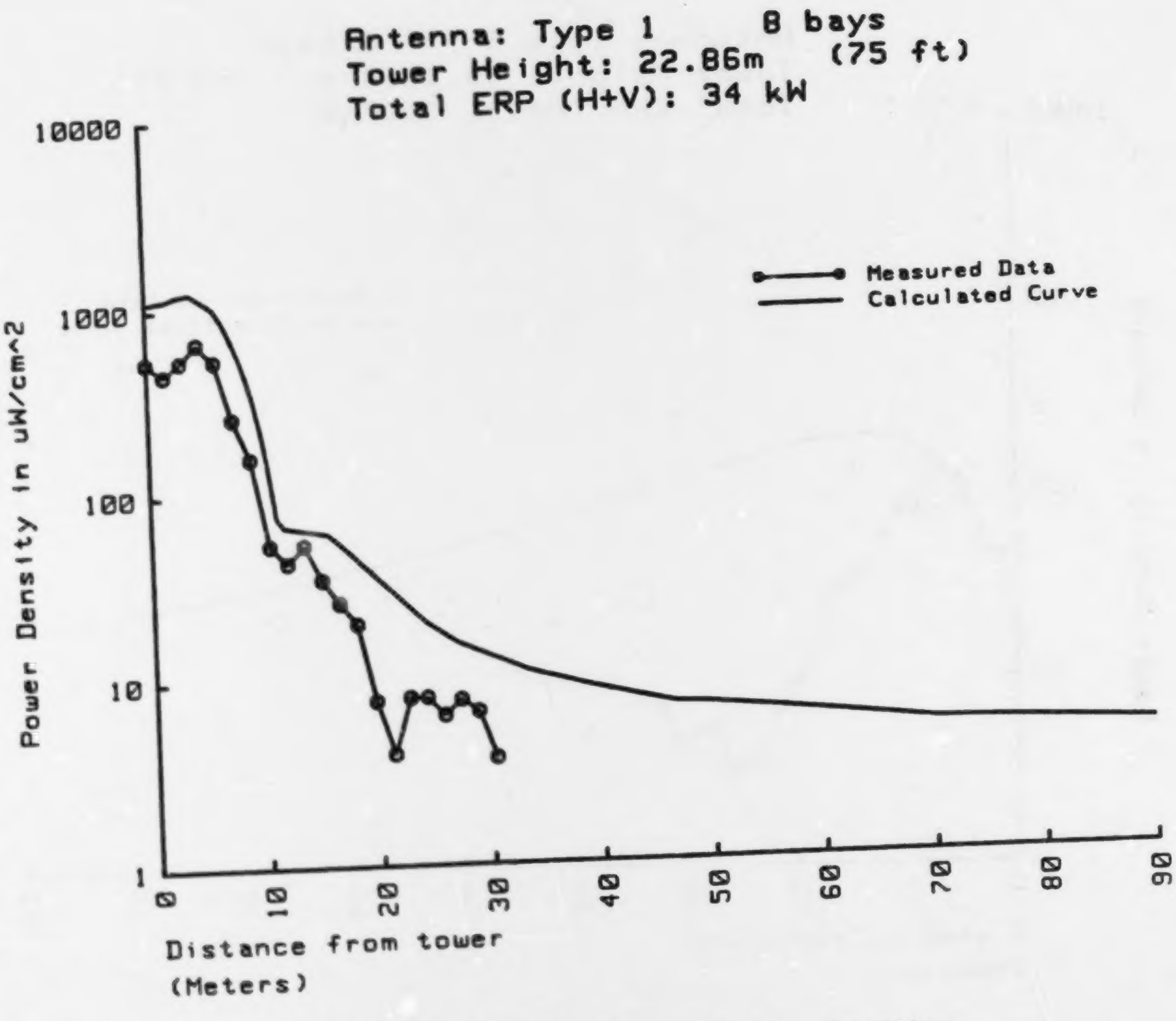


Figure 52. Calculated and measured power densities (free-space equivalent) for an actual FM station.

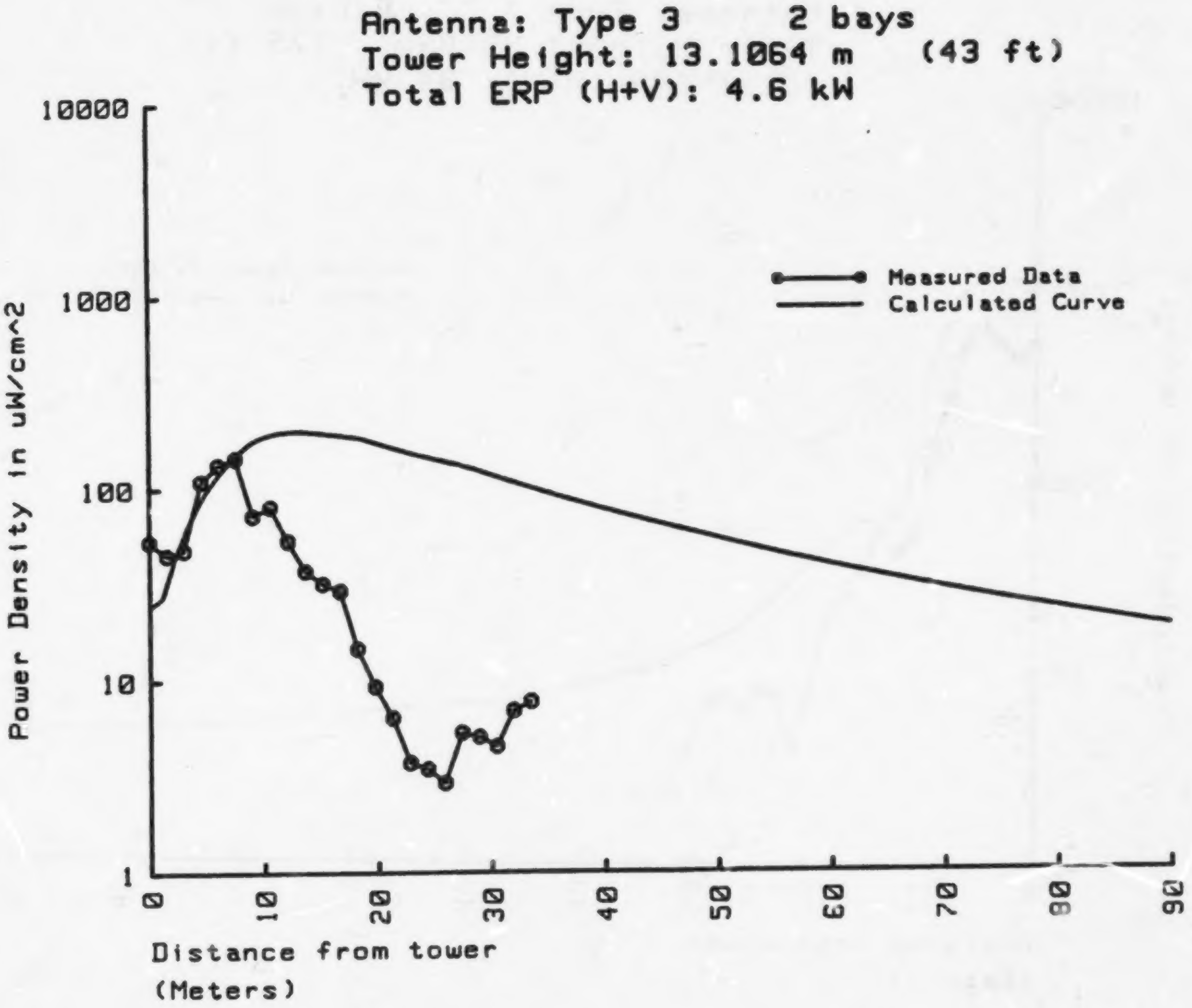


Figure 53. Calculated and measured power densities (free-space equivalent) for an actual FM station.

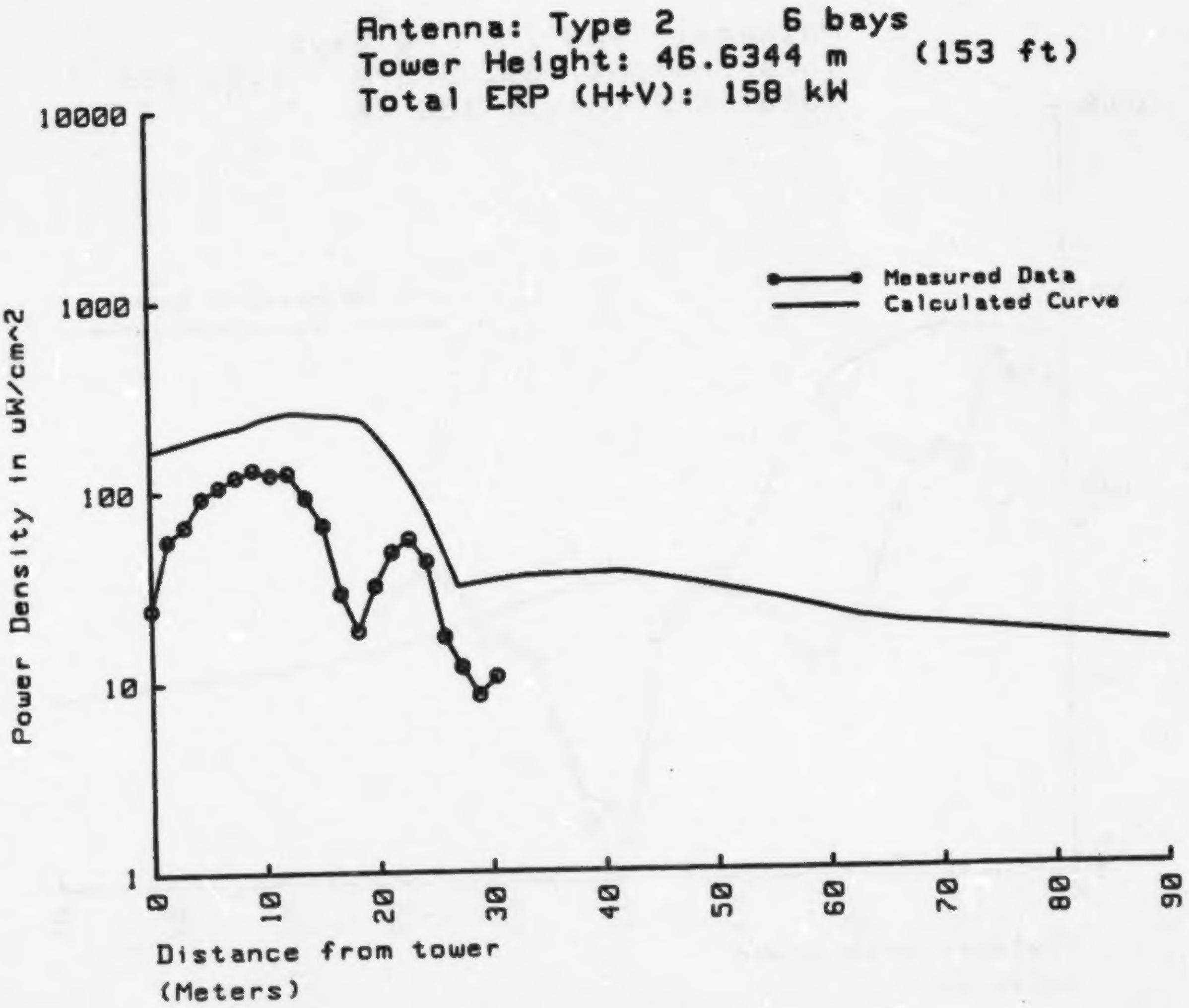


Figure 54. Calculated and measured power densities (free-space equivalent) for an actual FM station.

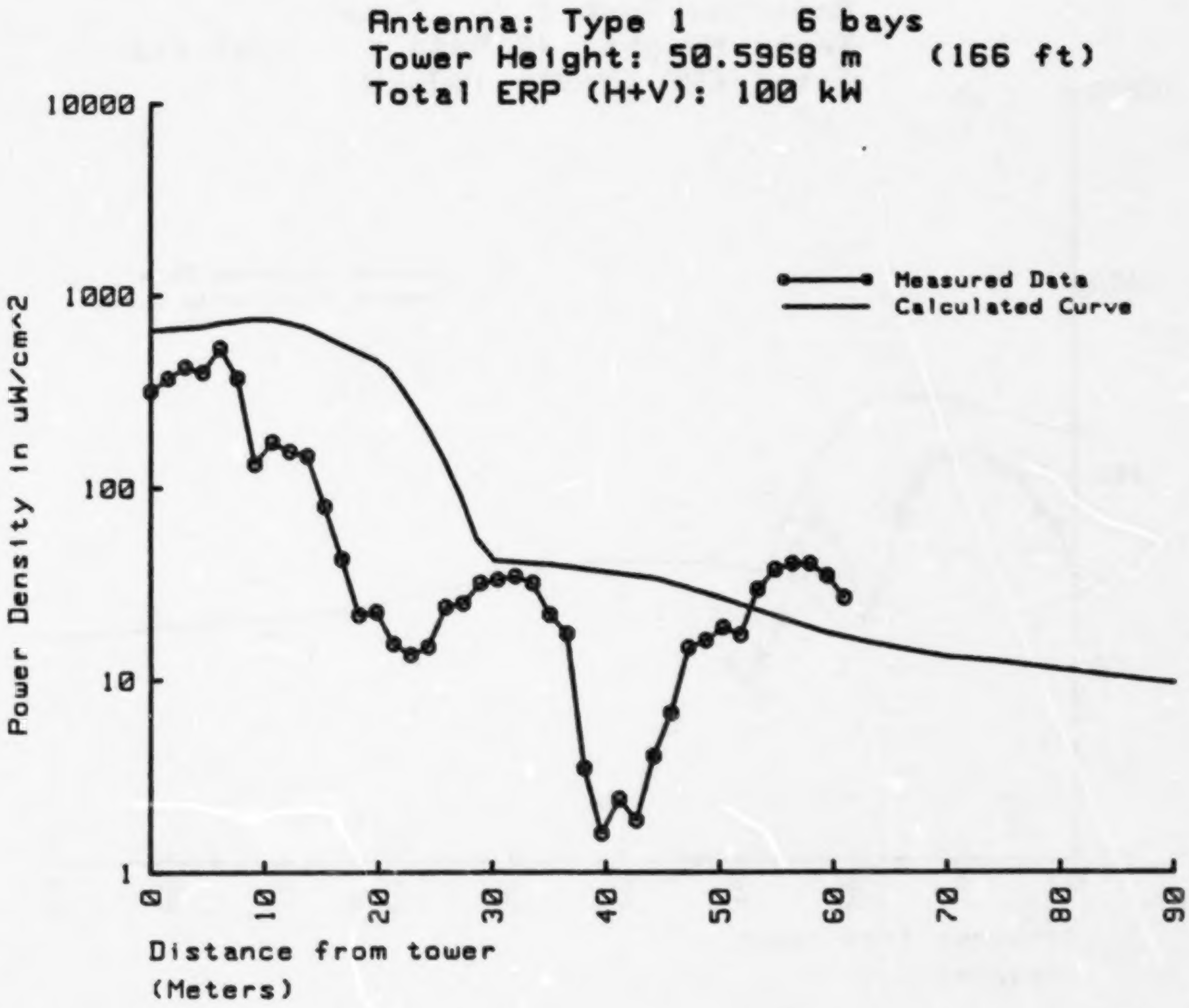


Figure 55. Calculated and measured power densities (free-space equivalent) for an actual FM station.

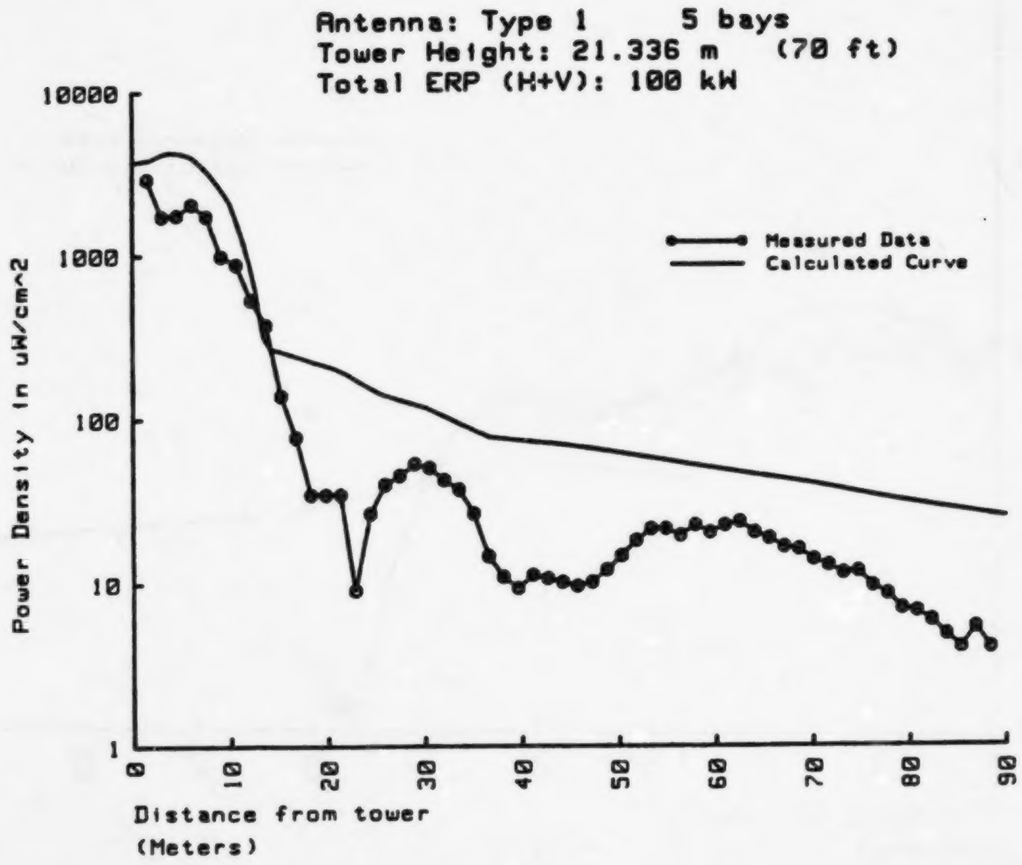


Figure 56. Calculated and measured power densities (free-space equivalent) for an actual FM station.

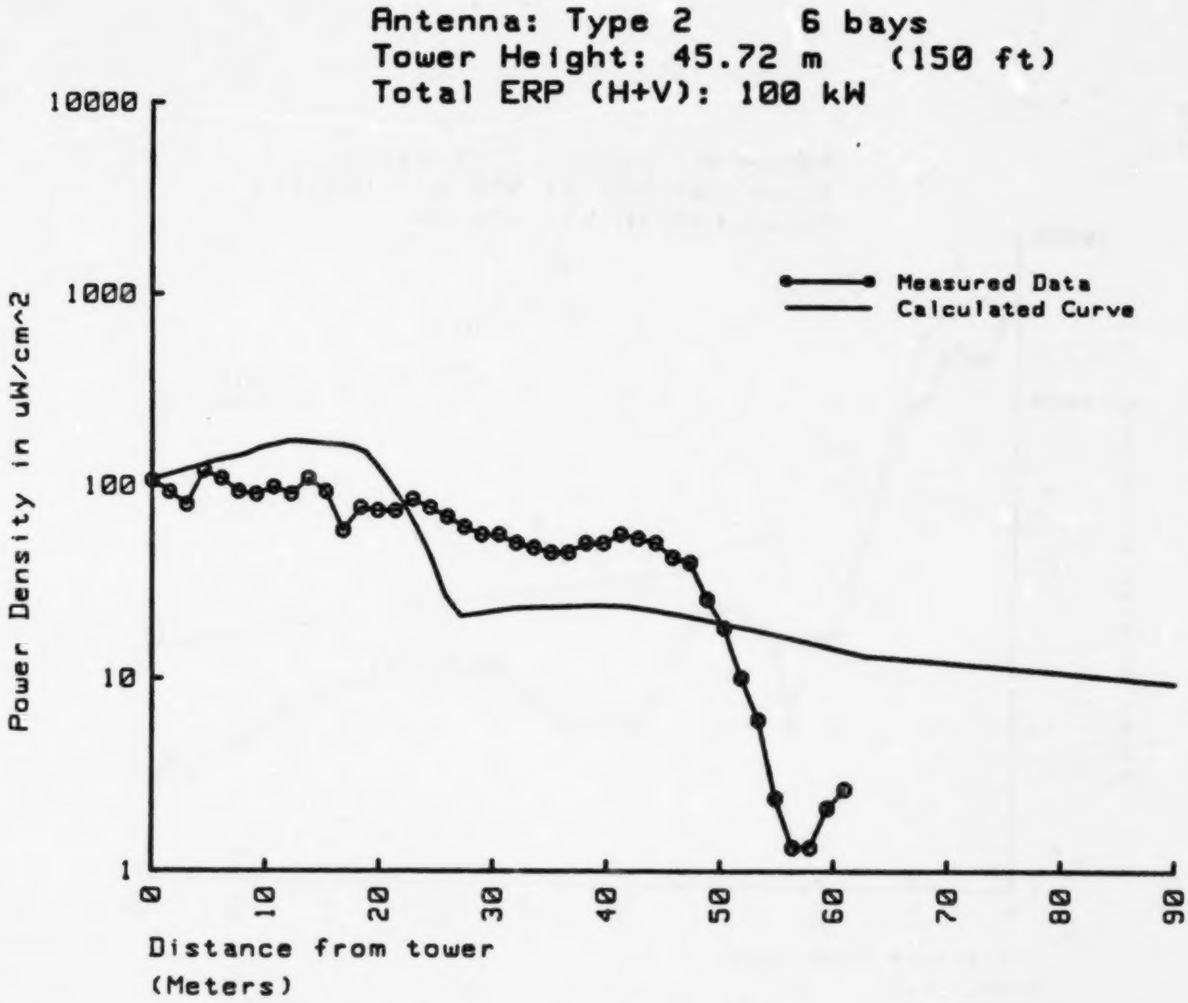
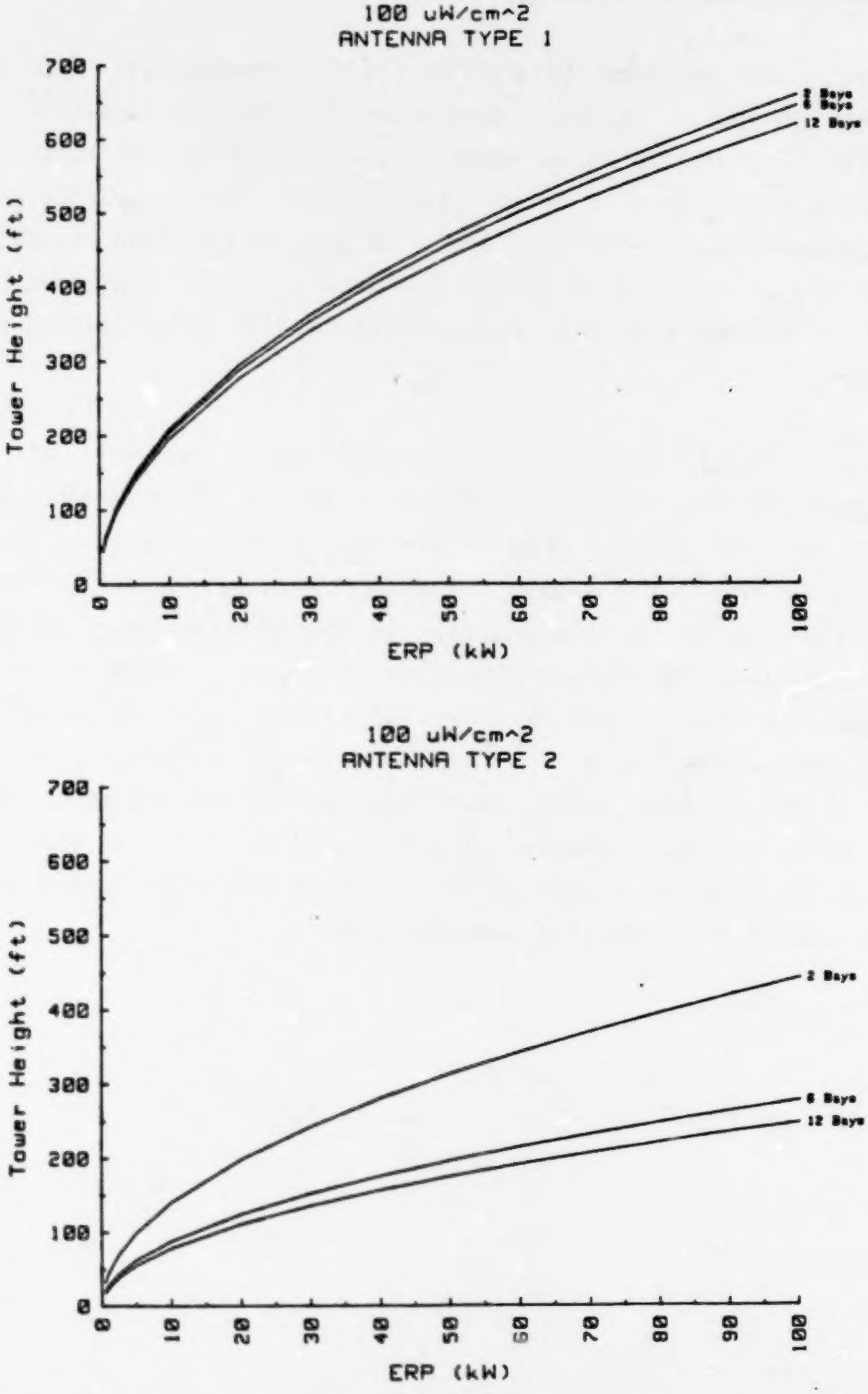


Figure 57. Calculated and measured power densities (free-space equivalent) for an actual FM station.

Appendix C - Minimum Tower Heights for FM's

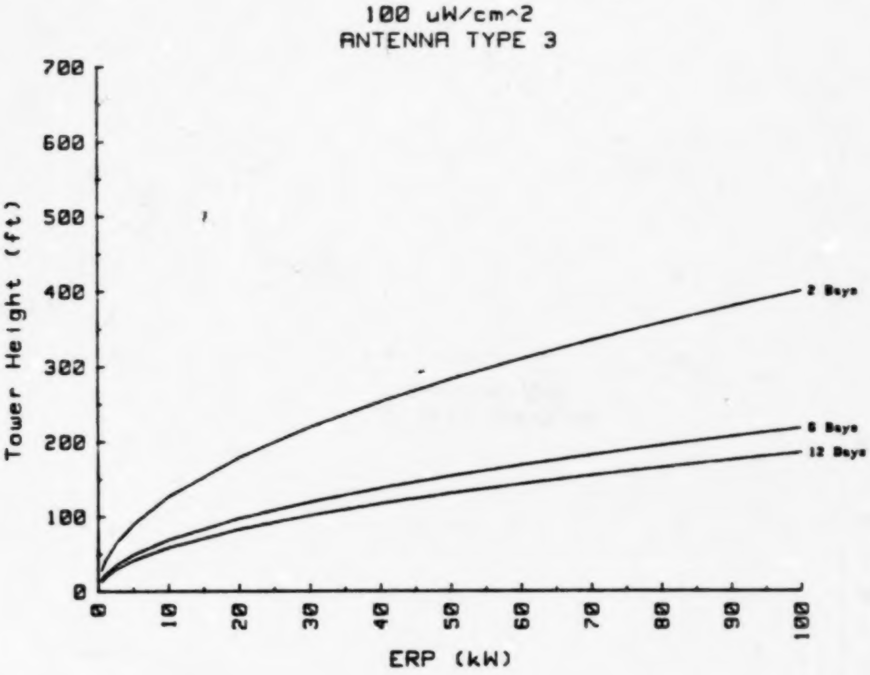
The FM model was designed to predict field strengths (as free space equivalent power densities) on the ground near FM broadcast facilities when given values for ERP, antenna type, tower height, and number of bays. This process can be inverted so that for a given antenna type, the model draws curves of the minimum tower heights necessary to prevent the creation of power densities exceeding an established limit. The x-axis is ERP ranging from 0 to 100 kW and it is assumed that this value occurs in both polarizations as is usually the case.

These graphs (Figure 58-69) are useful in making estimates of tower heights necessary to stay below a given power density. The graph labeled Type 1 antenna at 200 $\mu W/cm^2$, (Figure 60) for example, can be used by finding the station ERP on the x-axis and using the proper curve to find the corresponding tower height on the y-axis. If the station tower height is signficantly less than the height found on the graph, there is a good probability that equivalent power densities of greater than 200 $\mu W/cm^2$ will occur near the tower. Many assumptions were used in the formulation of the FM model, as described in this report, and there can be no guarantee of the accuracy of these graphs. However, the field study data in Appendix B indicates that the model is a good approximation to the upper bounds of the equivalent power densities occurring near the tower.


100 uW/cm^2
ANTENNA TYPE 1

100 uW/cm^2
ANTENNA TYPE 2

Figure 58. Minimum tower heights necessary to prevent creation of 100 $\mu W/cm^2$ on the ground.



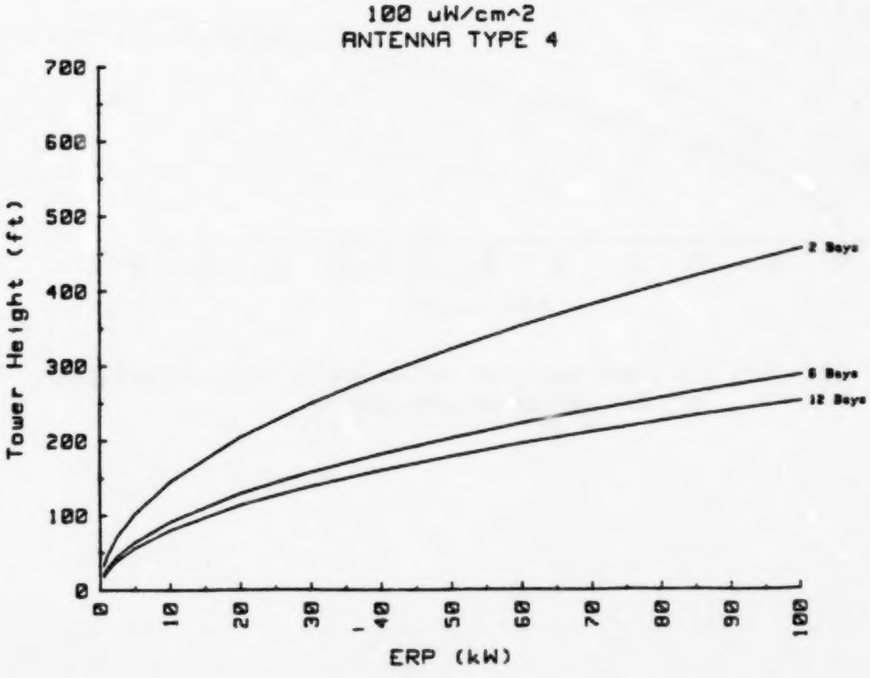
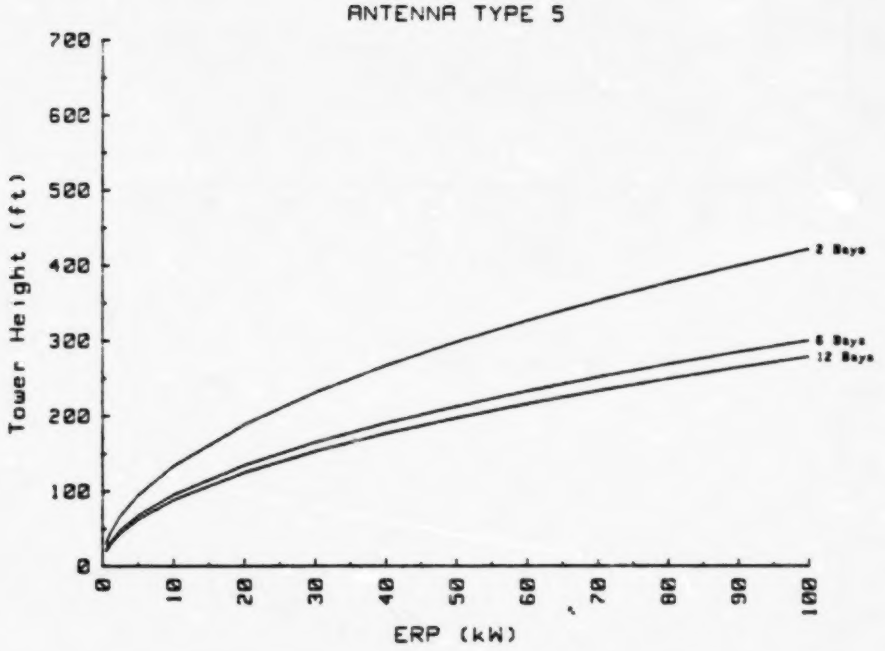


Figure 59. Minimum tower heights necessary to prevent creation of 100 μW/cm^2 on the ground.



100 uW/cm^2
ANTENNA TYPE 5

Figure 60. Minimum tower heights necessary to prevent creation of 100 μW/cm^2 on the ground.

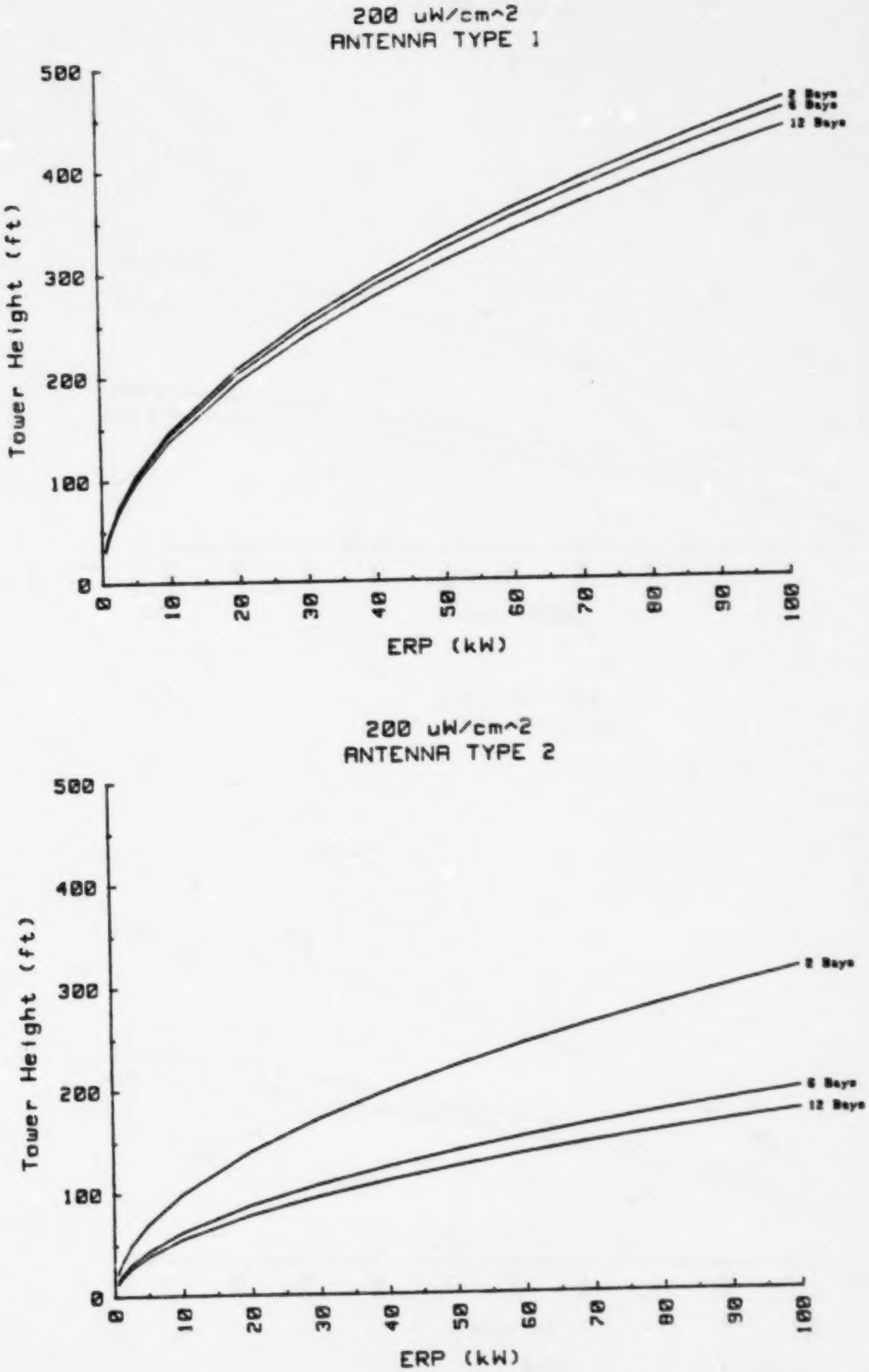


Figure 61. Minimum tower heights necessary to prevent creation of 200 μW/cm^2 on the ground.

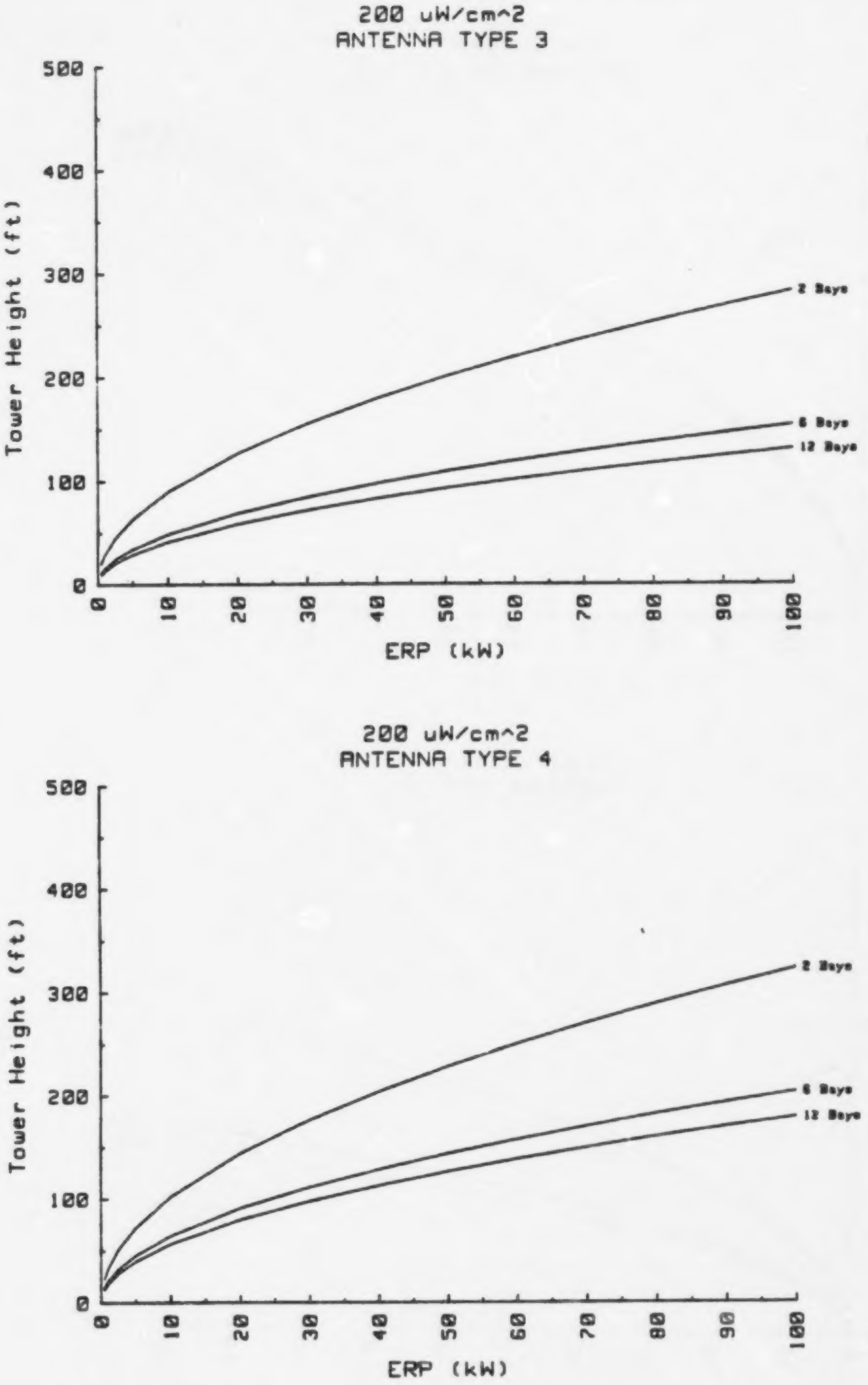


Figure 62. Minimum tower heights necessary to prevent creation of 200 μW/cm^2 on the ground.

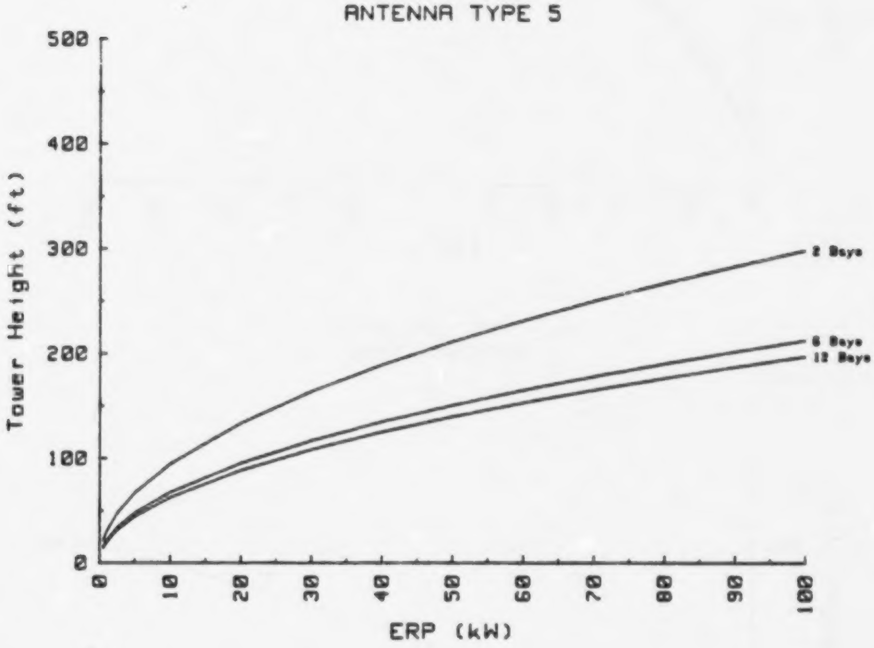
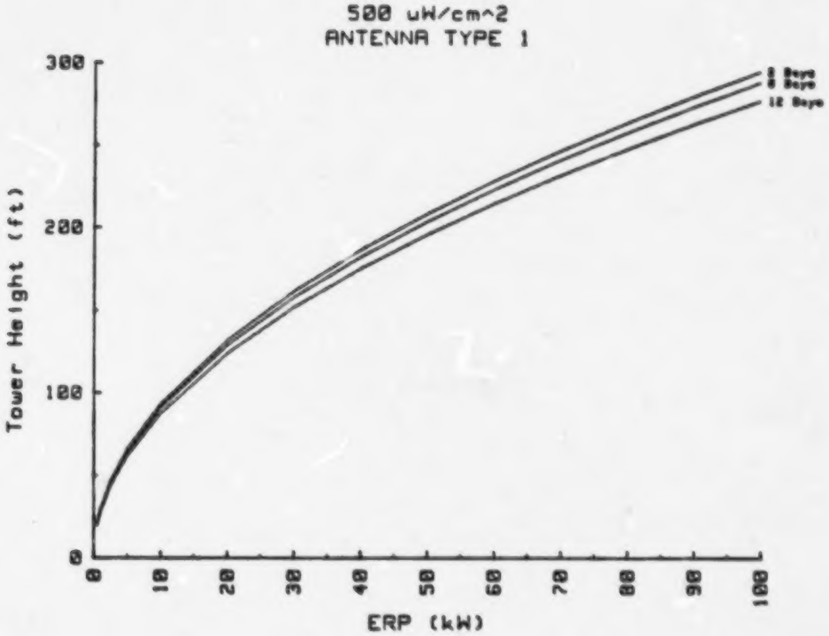


Figure 63. Minimum tower heights necessary to prevent creation of 200 μW/cm^2 on the ground.



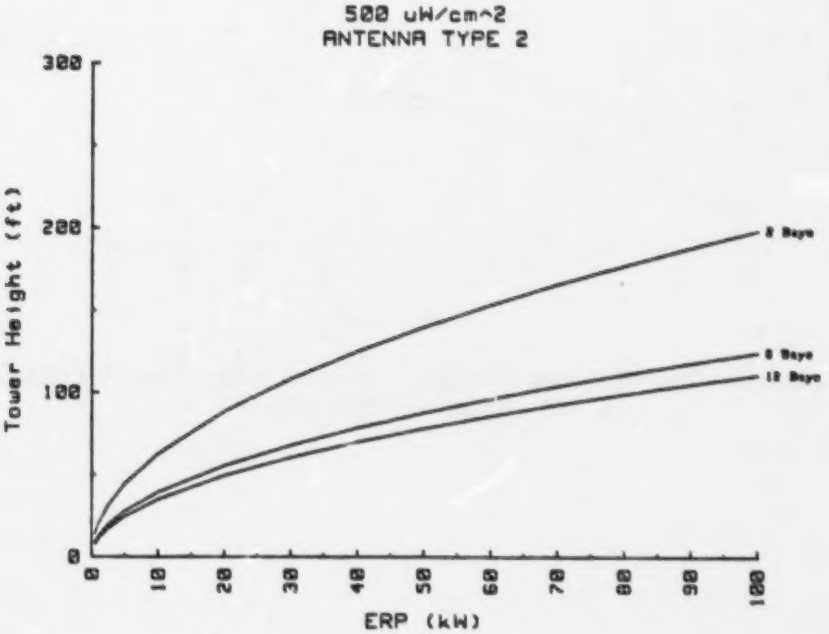


Figure 64. Minimum tower heights necessary to prevent creation of 500 μW/cm^2 on the ground.

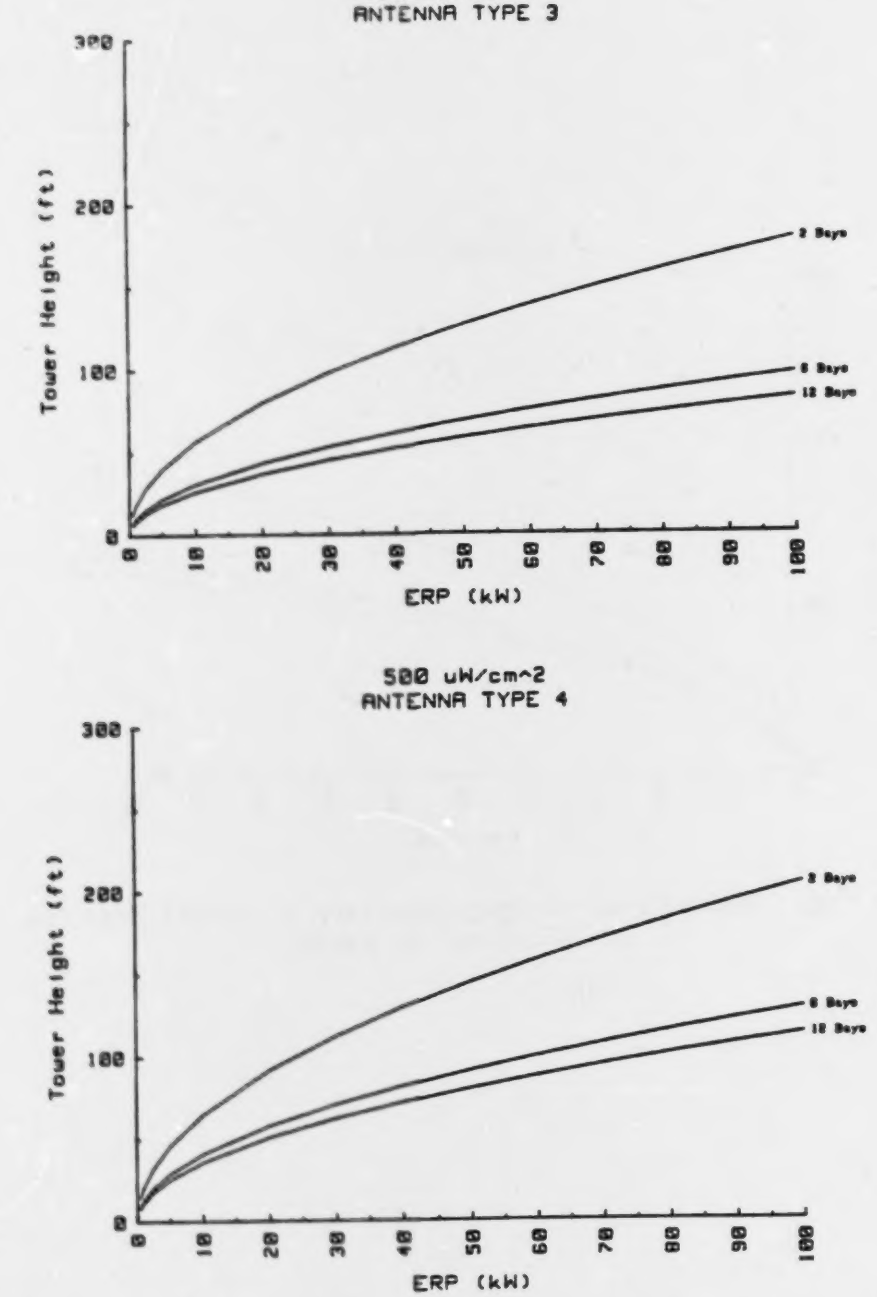


Figure 65. Minimum tower heights necessary to prevent creation of 500 μW/cm^2 on the ground.

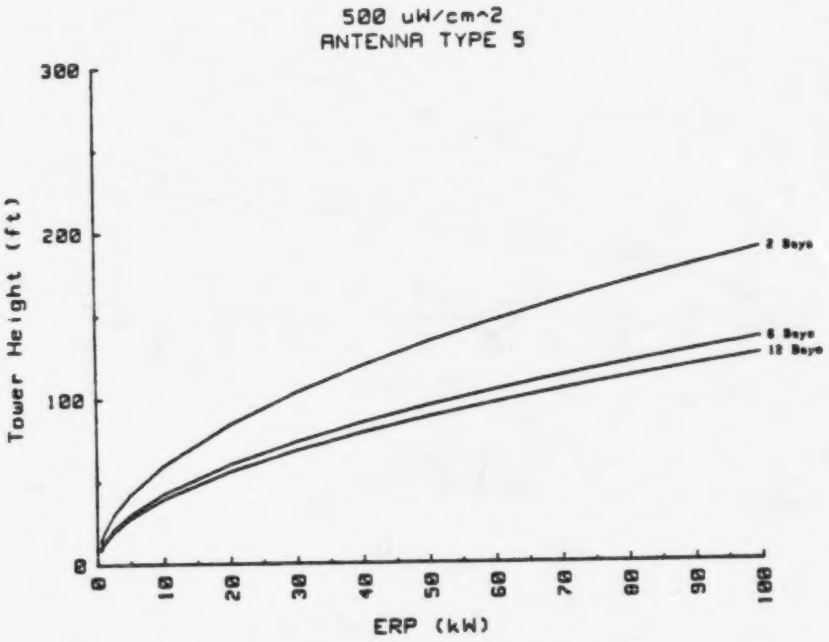
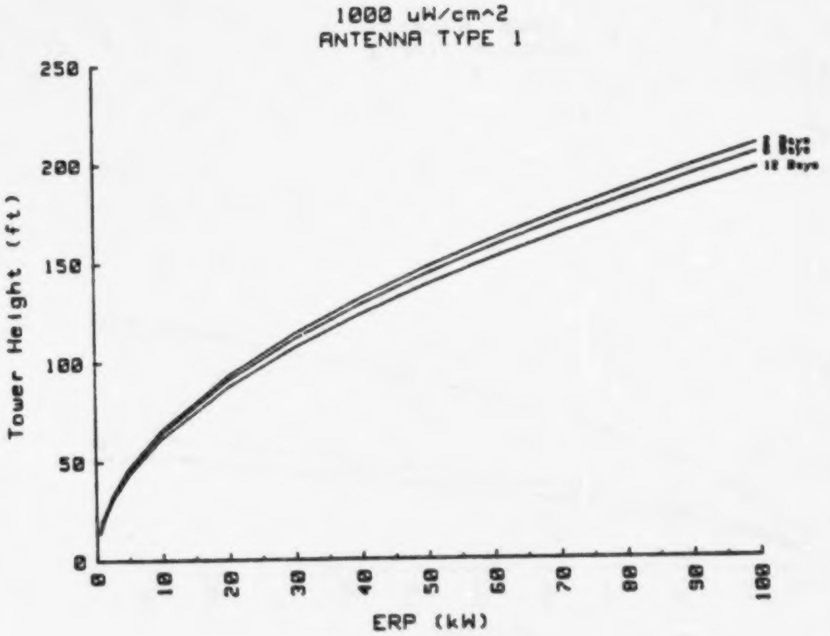


Figure 66. Minimum tower heights necessary to prevent creation of 500 $\mu W/cm^2$ on the ground.



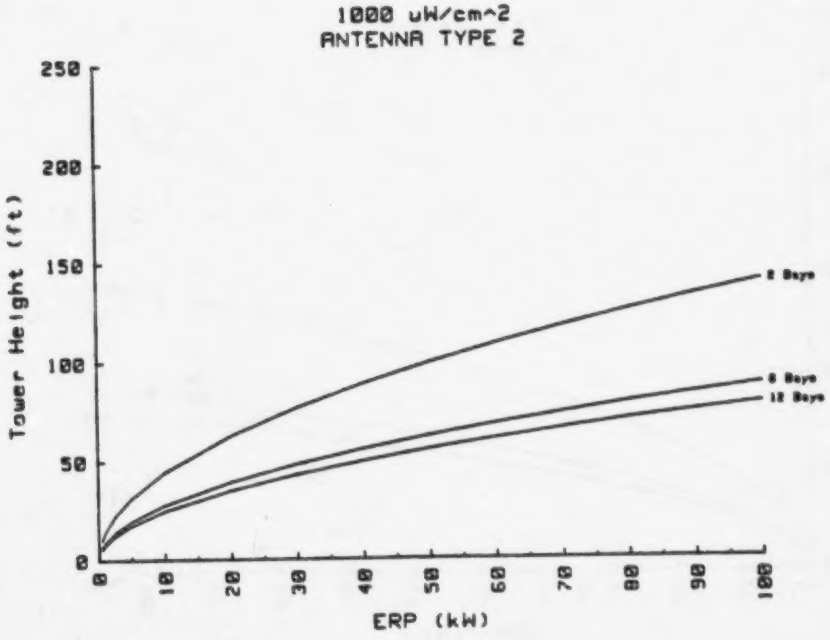
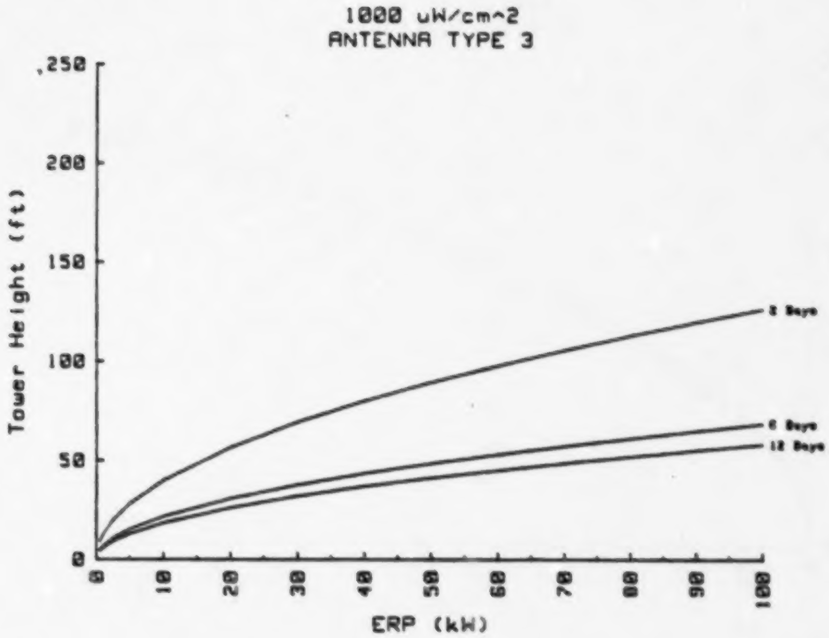


Figure 67. Minimum tower heights necessary to prevent creation of 1000 μW/cm^2 on the ground.



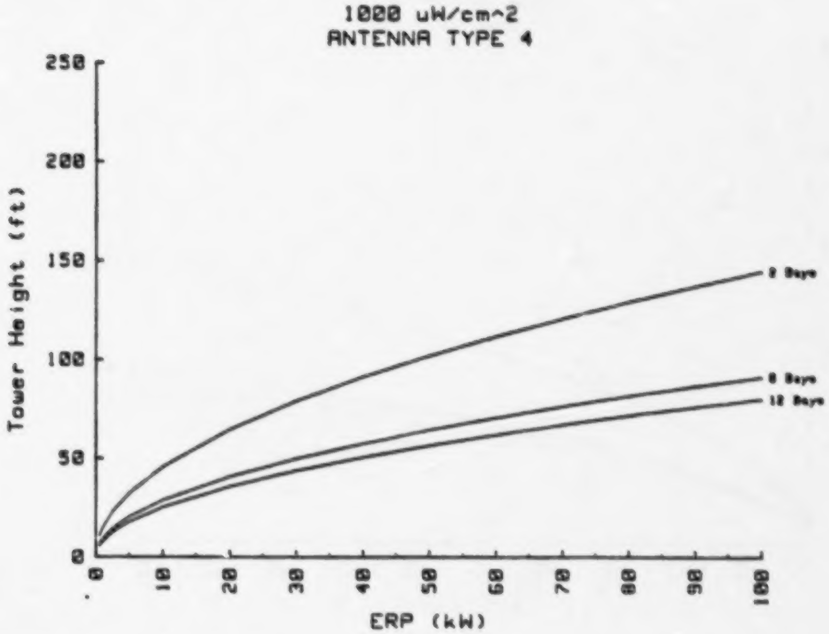


Figure 68. Minimum tower heights necessary to prevent creation of 1000 μW/cm^2 on the ground.

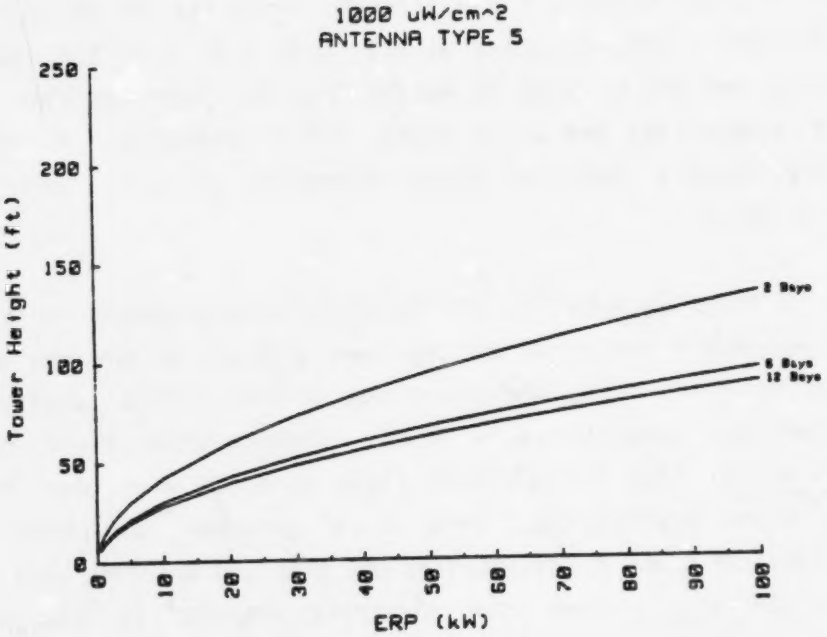


Figure 69. Minimum tower heights necessary to prevent creation of 1000 $\mu W/cm^2$ on the ground.

Appendix D - Predicted Field Strengths for AM stations

The modeling procedures for AM stations described in this report computed field strength values in the vicinity of single tower stations. Some of these results are shown in the following figures to illustrate typical field strength values found near AM transmitters and the trends described in the text.

Figure 70 shows electric field strength plots for 50 kW, 0.3 wavelength electrical height towers operating at 0.6, 0.8, 1.0, 1.2, 1.4, and 1.6 MHz. The curves coincide out to about 15 meters from the tower and then split apart with higher frequencies producing higher field strengths. Figure 71 is a similar plot showing magnetic field strengths produced under the same conditions as above.

Figure 72 shows the electric and magnetic field strengths for a 1 MHz, 50 kW, 0.3 wavelength electrical height tower plotted on the same graph. The electric and magnetic field strength scales of the vertical axes are related by the free-space condition $E = 377H$. The magnetic field strength is consistently higher than the electric field strength when they are compared using free space equivalence. This is a relevant comparison since the limiting values for E and H specified in the proposed Guidance will be related by $E_{max} = 377\ H_{max}$. When the electrical height is changed to 0.5 wavelength, neither field is consistently greater as shown in Figure 73. Thus both fields must be considered in impact modeling.

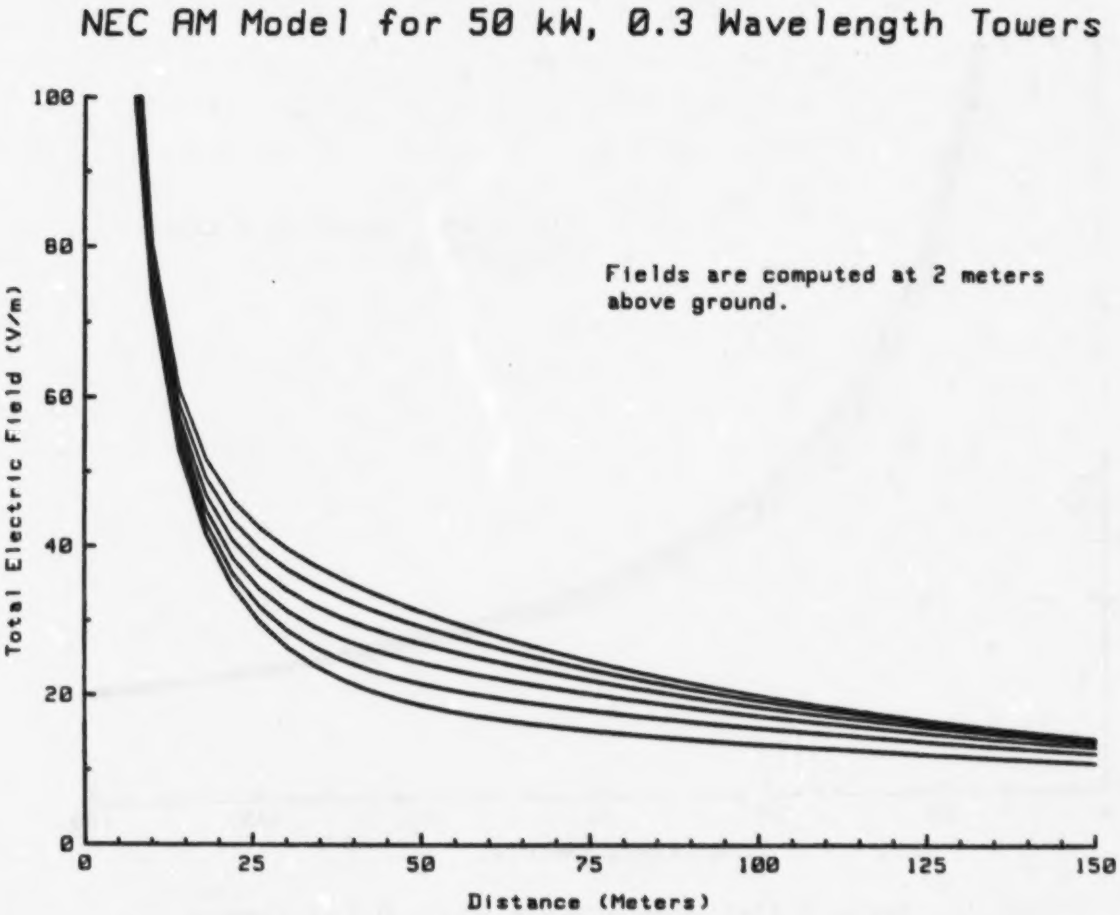


Figure 70. Electric field strengths for 50 kW, 0.3 wavelength electric height towers operating at 0.6, 0.8, 1.0, 1.2, 1.4 and 1.6 MHz. Higher frequencies produce higher field strengths.

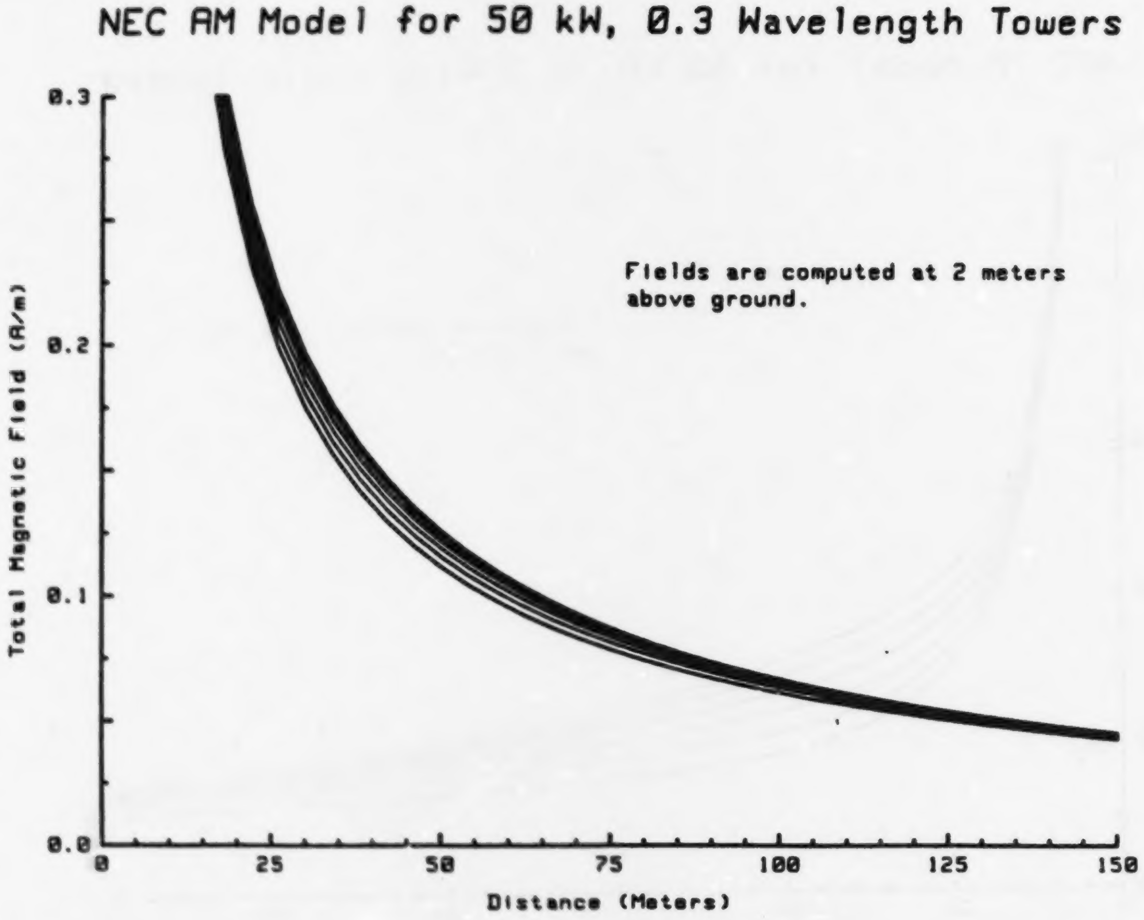


Figure 71. Magnetic field strengths for 50 kW, 0.3 wavelength electric height towers operating at 0.6, 0.8, 1.0, 1.2, 1.4, and 1.6 MHz. Higher frequencies produce higher field strengths.

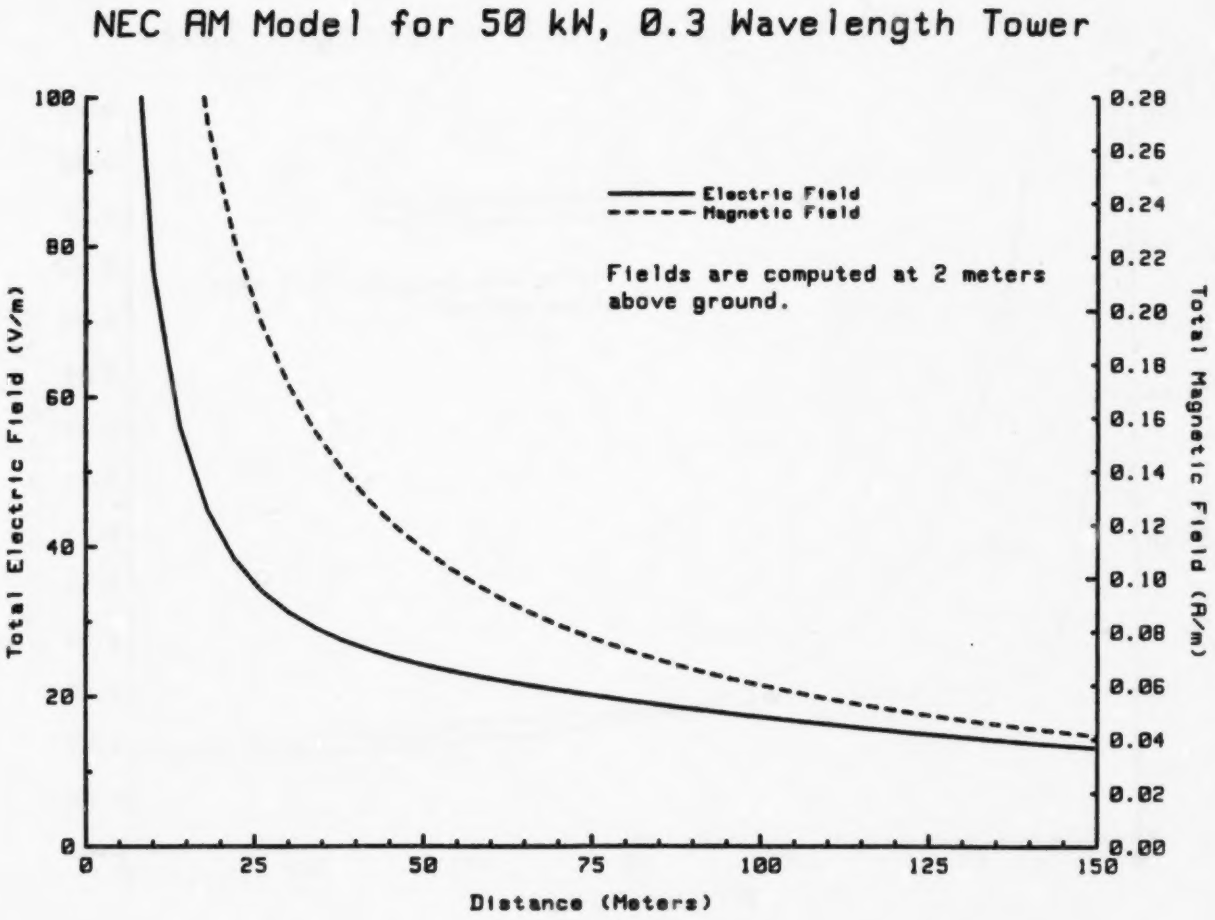


Figure 72. Electric and magnetic field strengths for a 50 kW, 0.3 wavelength tower.

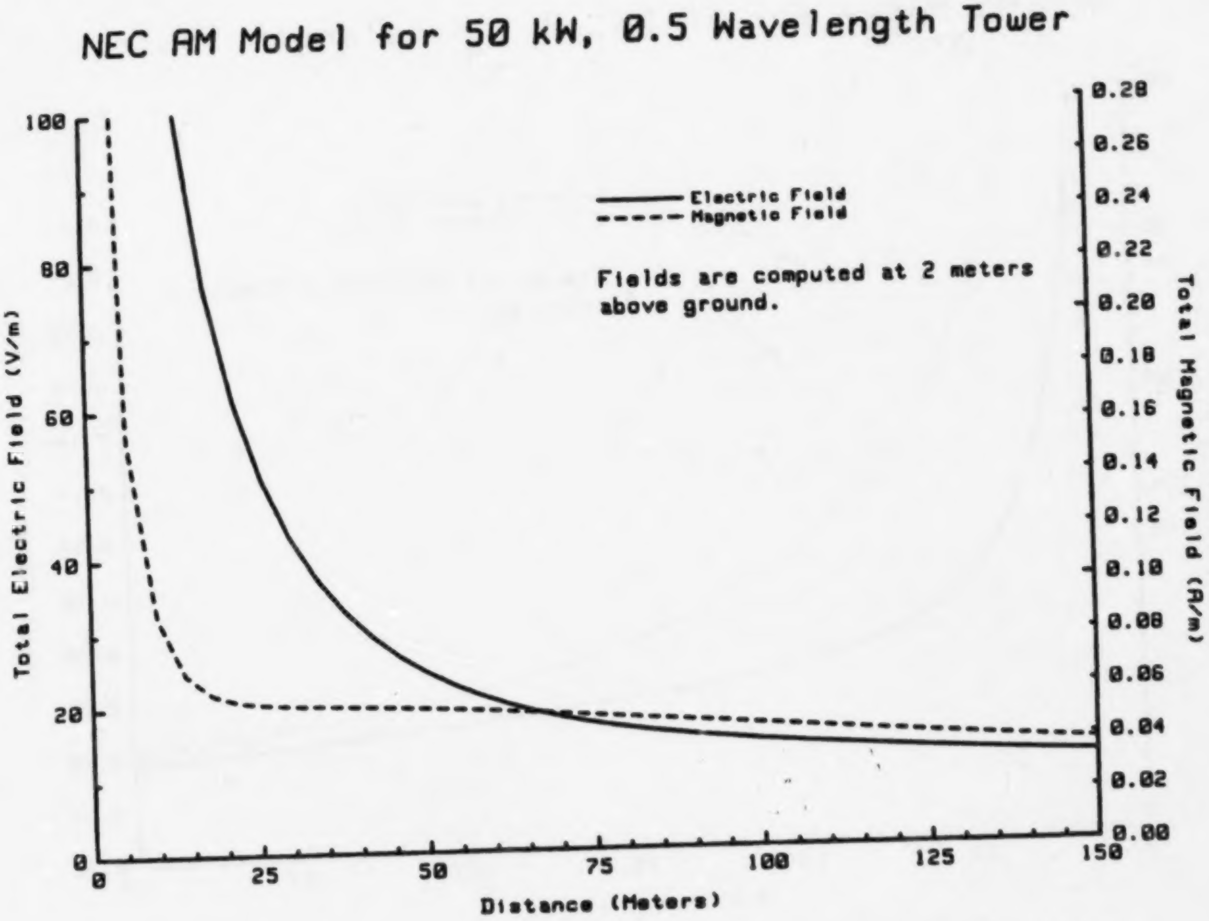


Figure 73. Electric and magnetic field strengths for a 50 kW, 0.5 wavelength tower.

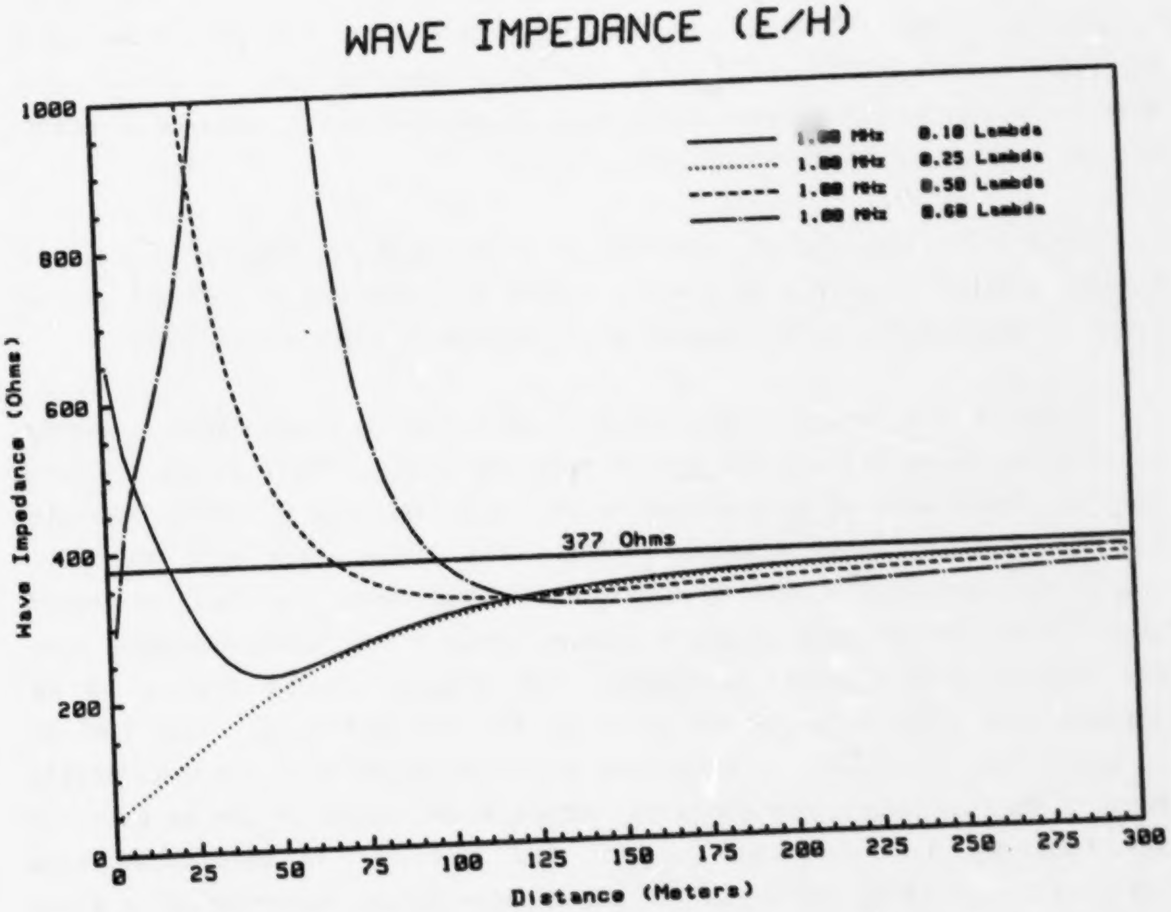


Figure 74. Wave impedance (E/H) for several different electrical heights at 1 MHz.

Although the curves in Figure 70 through 73 represent the fields from 50 kW stations, they can be used to predict fields from lower power stations as well. Figure 72, for example, shows that a 50 kW, 1 MHz, 0.30 wavelength electrical height transmitter produces about a 20 V/m electric field at 100 meters. A 10 kW station would produce an electric field of:

$$E = \sqrt{\frac{10\ \text{kW}}{50\ \text{kW}}} \quad \times \quad 20\ \text{V/m} \quad = \quad 8.9\ \text{V/m}$$

Figure 74 shows wave impedance (E/H) for several different electrical heights at 1 MHz. This graph illustrates the fact that the free-space impedance condition (E/H = 377) does not occur near the tower in most cases. Both the electric and magnetic field must be considered for guidance purposes whether one is measuring or calculating fields.

Figure 75 is a plot of electric field strength for several electrical heights holding frequency and power constant at 1 MHz and 50 kW. No simple trend is apparent for field strength as a function of electrical heights.

Table 53 is a sample of the distances away from AM transmitters necessary to avoid exceeding various alternative guidance levels. These values are from the four dimensional array described in the text (see page 62) which accounts for both electric and magnetic fields. The fields from a 1 MHz, 0.2 wavelength electrical height AM station will drop below the field strengths shown in the row headings at the distances shown in the table depending upon the station power (column headings). For example, fields from a 10 kW stations will drop below 100 V/m ($E < 100$ V/m and $(377 \times H) < 100$ V/m) at 14 meters from the tower. Although the distances in Table 53 are specifically for a 1 MHz, 0.2 wavelength electrical height tower, Table 54 can be used for any frequency and electrical height. The distances in this table were obtained by searching the array for the highest values occurring at a given power and field strength. They are the greatest distances necessary to fall below the specified guidance levels for any frequency and electrical height. More simply, Table 54 shows the worst case distances necessary to comply with the specified alternative guidance levels. In most cases, actual distances will be somewhat less than those shown in the table.

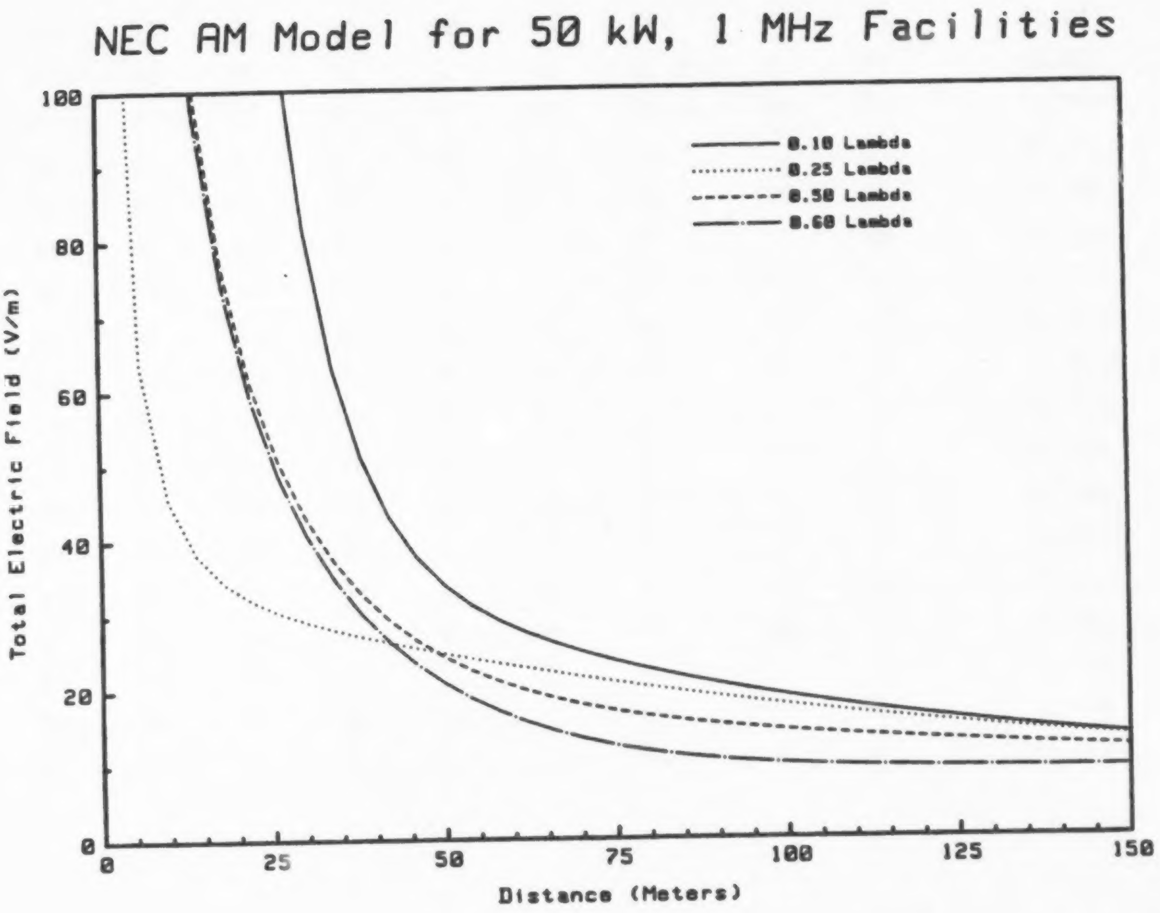


Figure 75. Electric field strength for several different electric heights at 1 MHz and 50 kW.

TABLE 53. DISTANCES (IN METERS) AT WHICH FIELDS FROM A 1 MHz 0.2 ELECTRICAL HEIGHT AM STATION WILL FALL BELOW EIGHTEEN ALTERNATIVE GUIDANCE LEVELS

Electric Field Strength	Transmitter Power (kW)								
V/m	50.00	25.00	10.00	5.00	2.50	1.00	0.50	0.25	0.10
10.00	222	158	102	74	54	38	26	22	14
31.62	74	54	38	26	22	14	10	10	6
44.67	54	42	26	22	14	10	10	6	6
70.79	38	26	18	14	10	6	6	6	<2
86.60	30	22	14	14	10	6	6	6	<2
100.00	26	22	14	10	10	6	6	6	<2
141.25	22	14	10	10	6	6	6	<2	<2
173.18	18	14	10	6	6	6	<2	<2	<2
200.00	14	10	10	6	6	6	<2	<2	<2
223.87	14	10	6	6	6	<2	<2	<2	<2
244.91	14	10	6	6	6	<2	<2	<2	<2
264.55	14	10	6	6	6	<2	<2	<2	<2
281.84	10	10	6	6	6	<2	<2	<2	<2
300.00	10	10	6	6	6	<2	<2	<2	<2
316.23	10	10	6	6	6	<2	<2	<2	<2
446.68	10	6	6	6	<2	<2	<2	<2	<2
707.95	6	6	<2	<2	<2	<2	<2	<2	<2
1000.00	6	6	<2	<2	<2	<2	<2	<2	<2

TABLE 54. DISTANCES (IN METERS) AT WHICH FIELDS FROM AM STATIONS WILL FALL BELOW EIGHTEEN ALTERNATIVE GUIDANCE LEVELS. THIS TABLE APPLIES TO ANY FREQUENCY OR ELECTRICAL HEIGHT

Electric Field Strength V/m	Transmitter Power (kW)								
	50.00	25.00	10.00	5.00	2.50	1.00	0.50	0.25	0.10
10.00	270	174	114	90	70	50	38	30	26
31.62	90	70	50	38	30	26	22	18	14
44.67	70	54	38	30	26	22	18	14	10
70.79	50	38	30	26	22	14	14	10	6
86.60	42	34	26	22	18	14	10	10	6
100.00	38	30	26	22	18	14	10	10	6
141.25	30	26	22	18	14	10	10	6	6
173.18	30	22	18	14	10	10	6	6	6
200.00	26	22	18	14	10	10	6	6	6
223.87	26	22	14	14	10	6	6	6	6
244.91	22	18	14	10	10	6	6	6	6
264.55	22	18	14	10	10	6	6	6	<2
281.84	22	18	14	10	10	6	6	6	<2
300.00	22	18	14	10	10	6	6	6	<2
316.23	22	18	14	10	10	6	6	6	<2
446.68	18	14	10	6	6	6	6	<2	<2
707.95	14	10	6	6	6	6	<2	<2	<2
1000.00	10	10	6	6	6	<2	<2	<2	<2

Appendix E

The output from the FM model is more specific than the summarized results presented in Tables 6 through 43. As indicated in Figure 13, the model also calculates the farthest distance from the station at which each of 18 alternative power density levels is exceeded. This information is useful in determining property or fencing requirements in order to comply with a given guidance level. Figures 76 through 85 are histograms illustrating the percentages of stations exceeding each guidance level at various distance intervals. The results for single ground mounted stations are presented in Figures 76 through 80. Figures 81 through 85 show the results for multiple ground mounted stations.

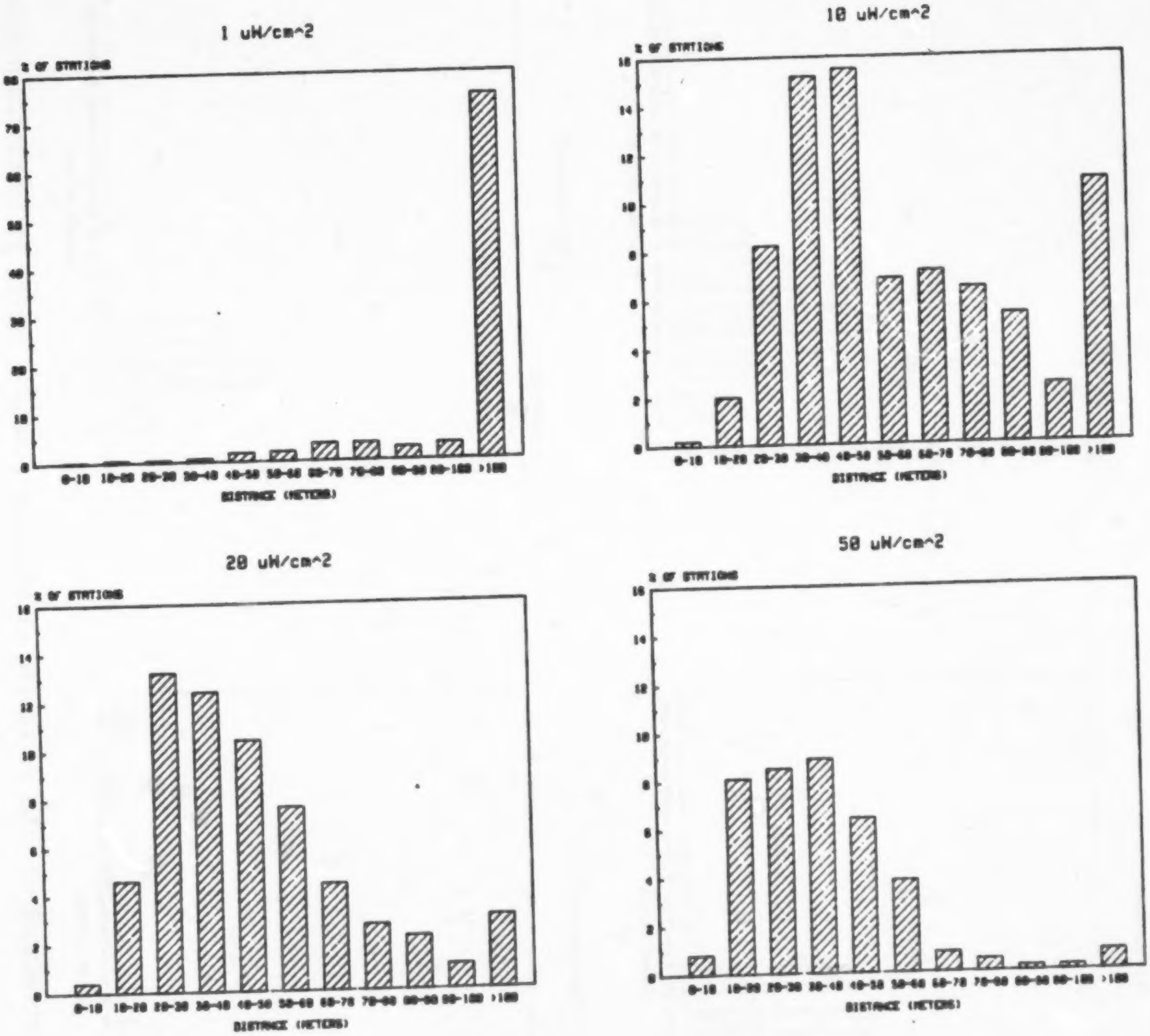


Figure 76. Percentages of SFMG exceeding alternative guidance levels to specified distances.

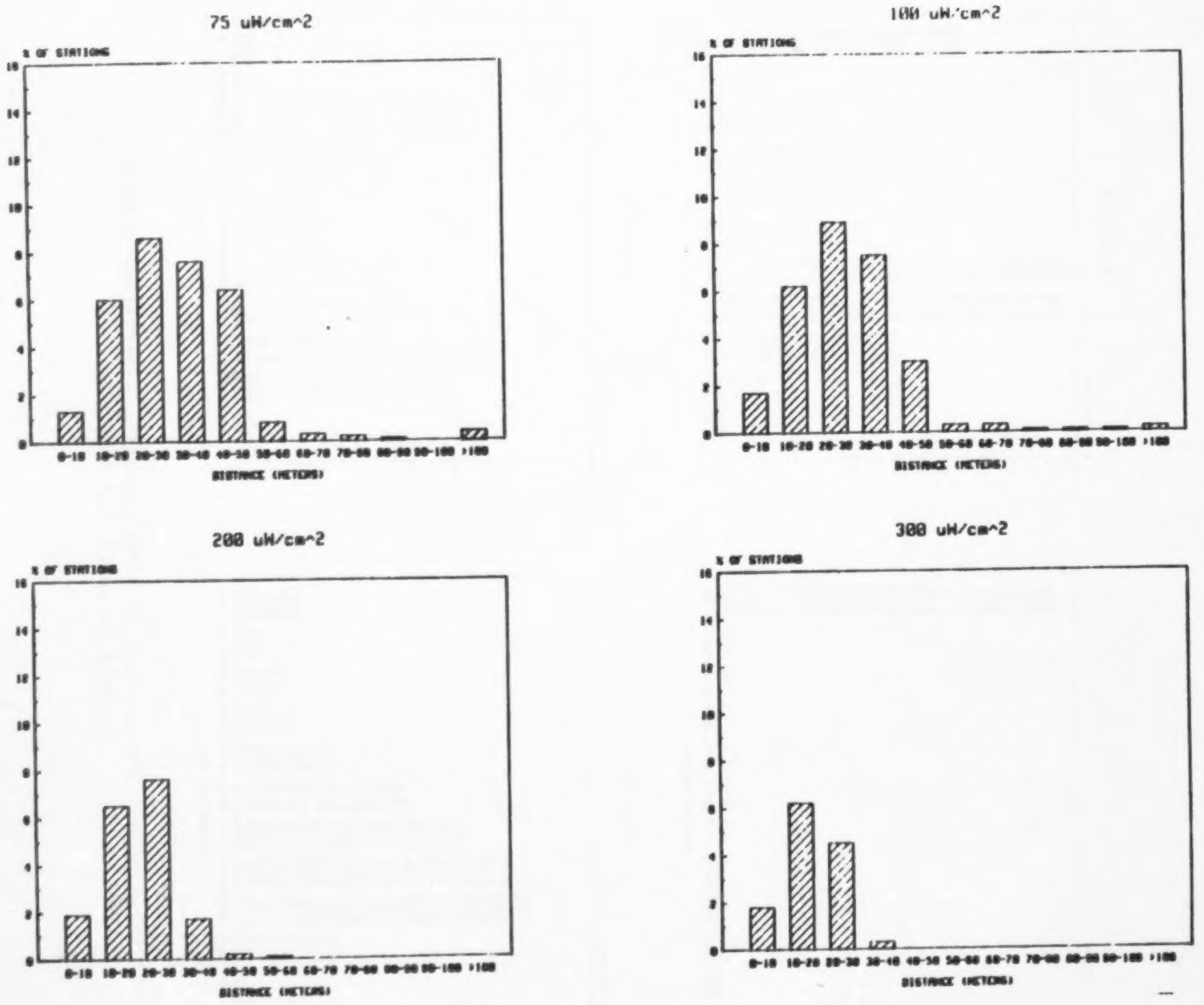


Figure 77. Percentages of SFMG exceeding alternative guidance levels to specified distances.

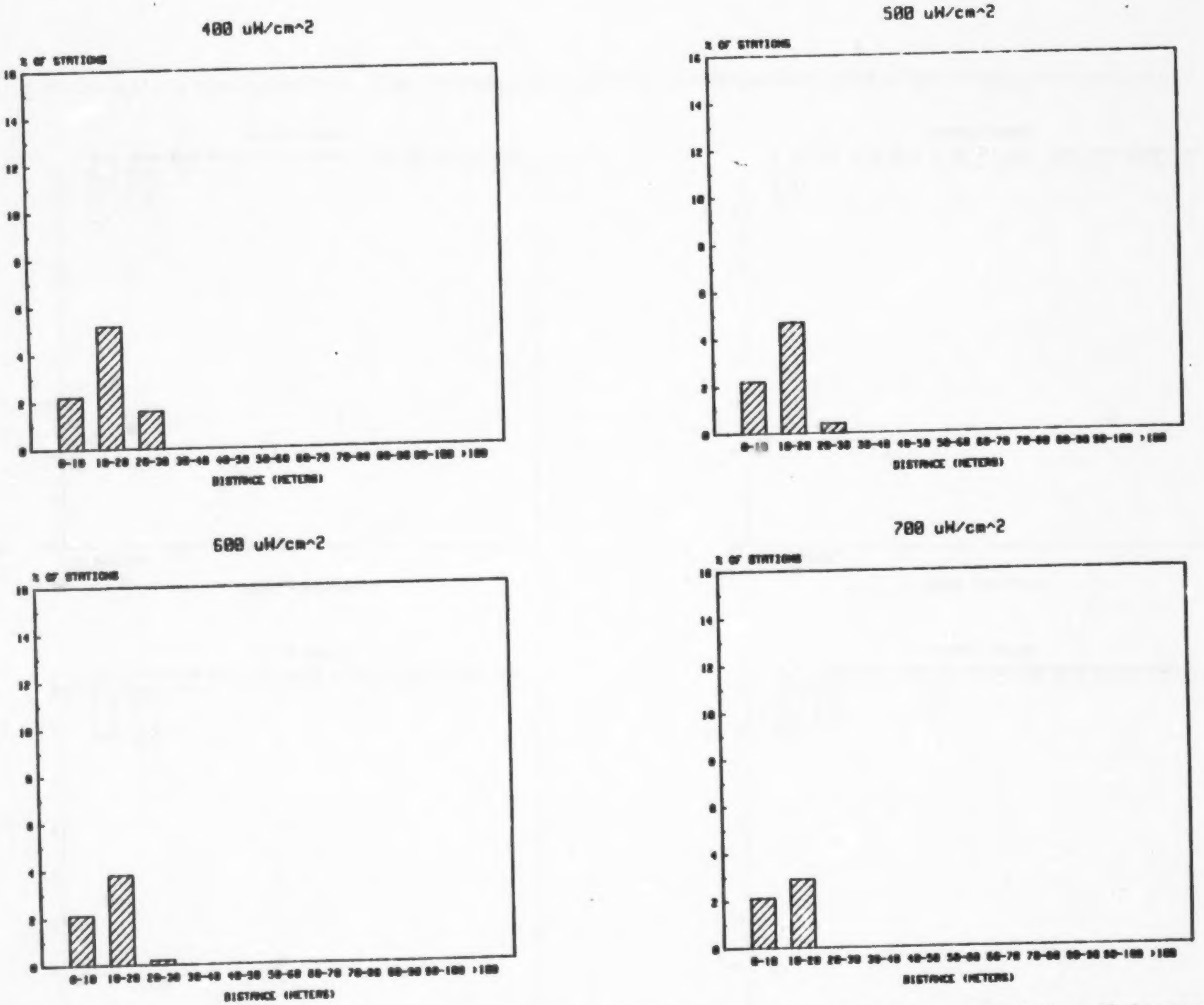


Figure 78. Percentages of SFMG exceeding alternative guidance levels to specified distances.

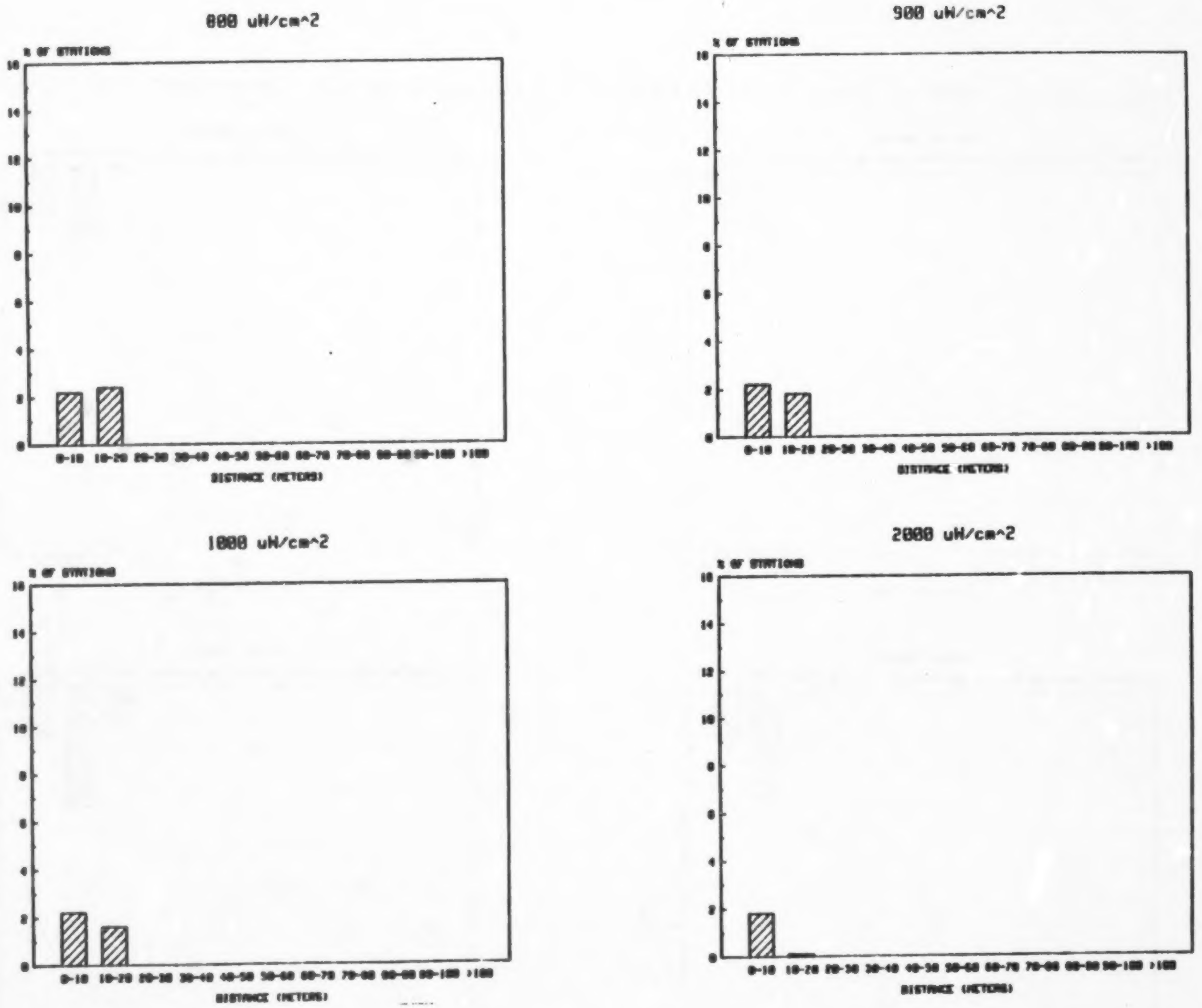


Figure 79. Percentages of SFMG exceeding alternative guidance levels to specified distances.

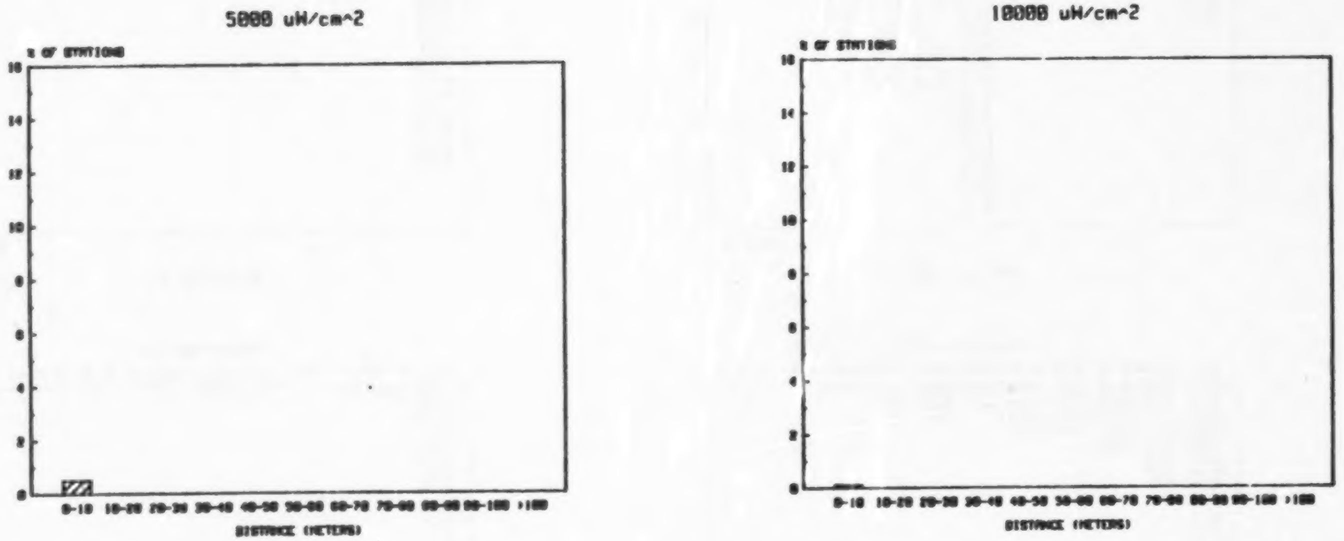


Figure 80. Percentages of SFMG exceeding alternative guidance levels to specified distances.

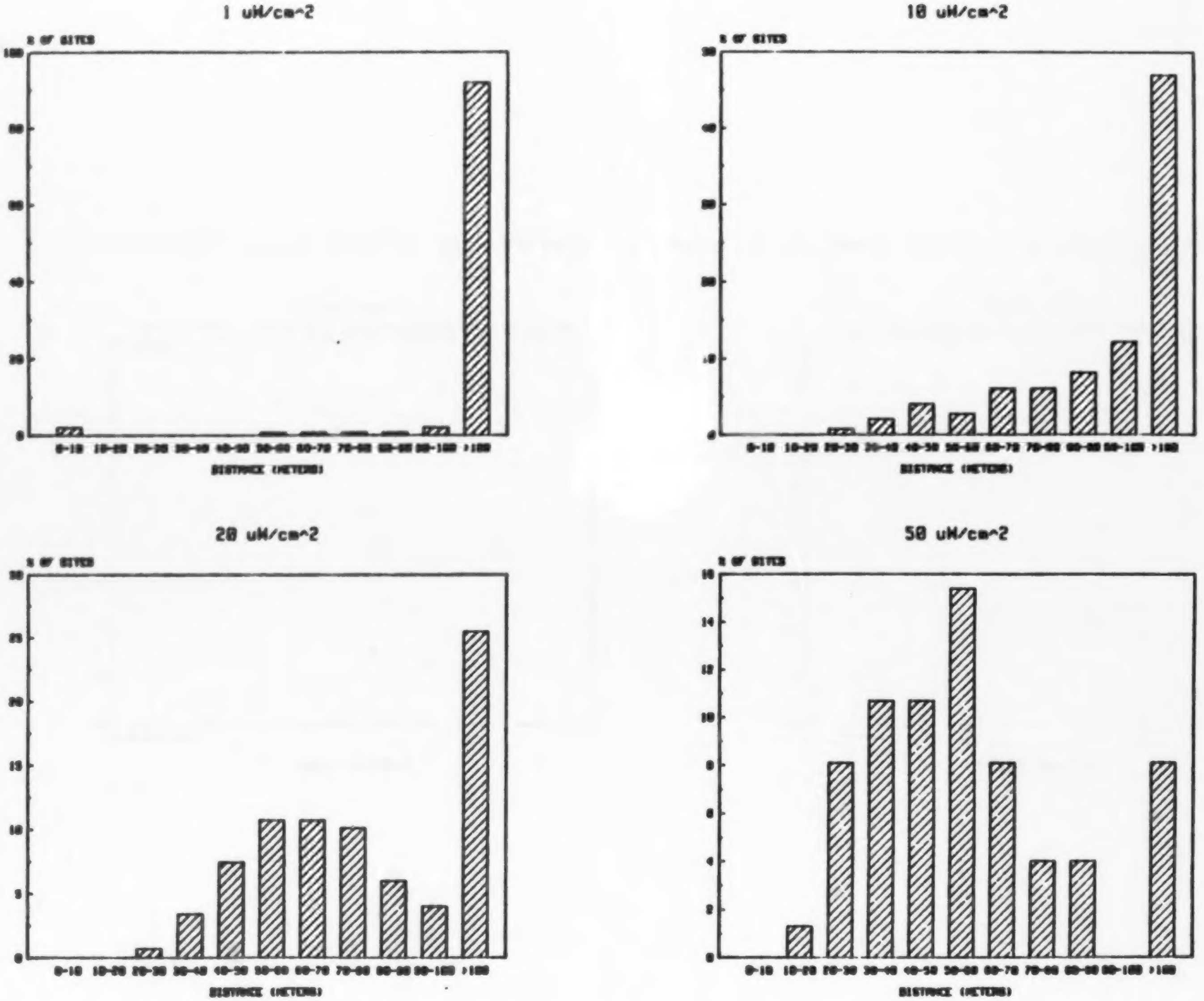


Figure 81. Percentages of MFMG exceeding alternative guidance levels to specified distances.

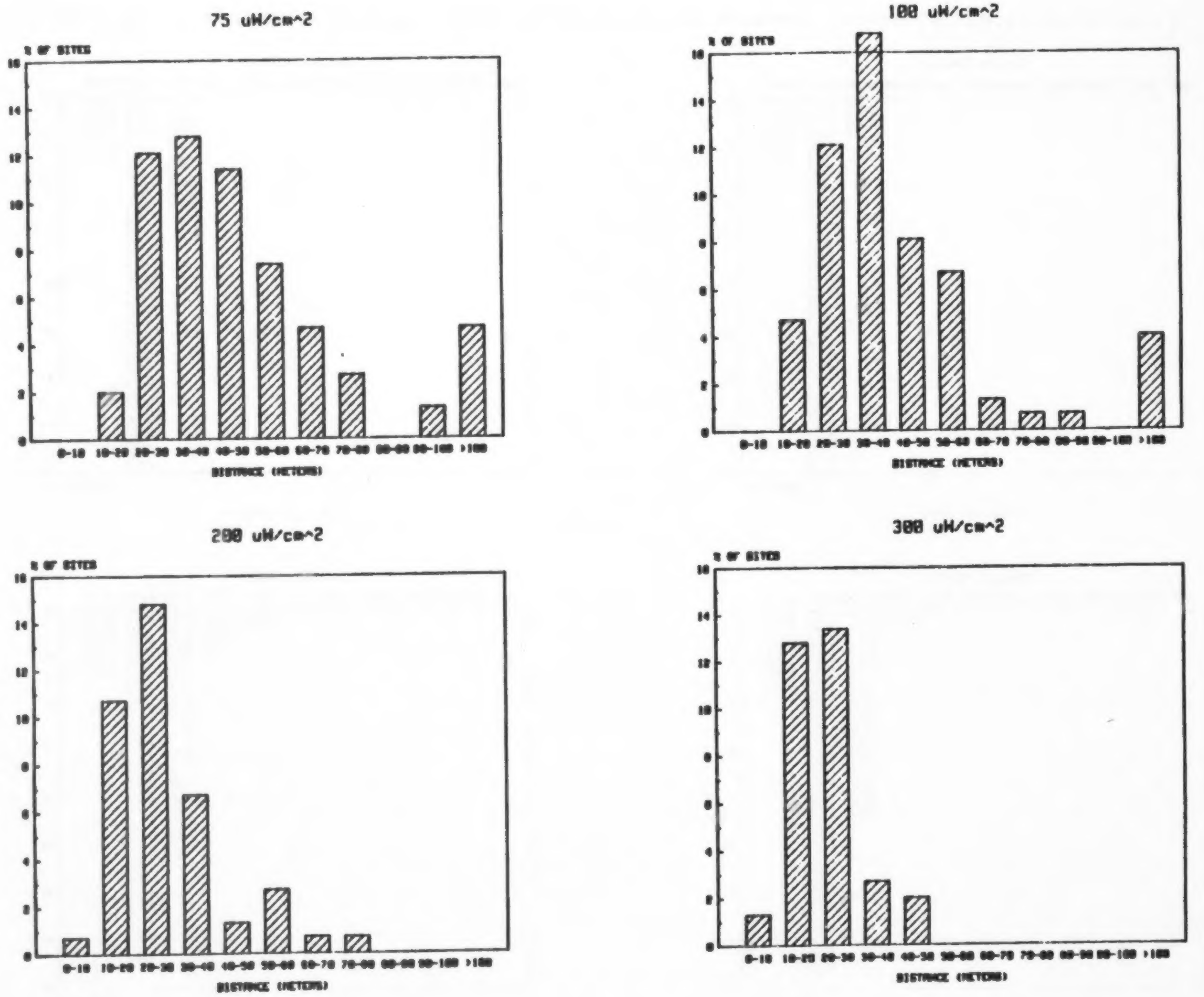


Figure 82. Percentages of MFMG exceeding alternative guidance levels to specified distances.

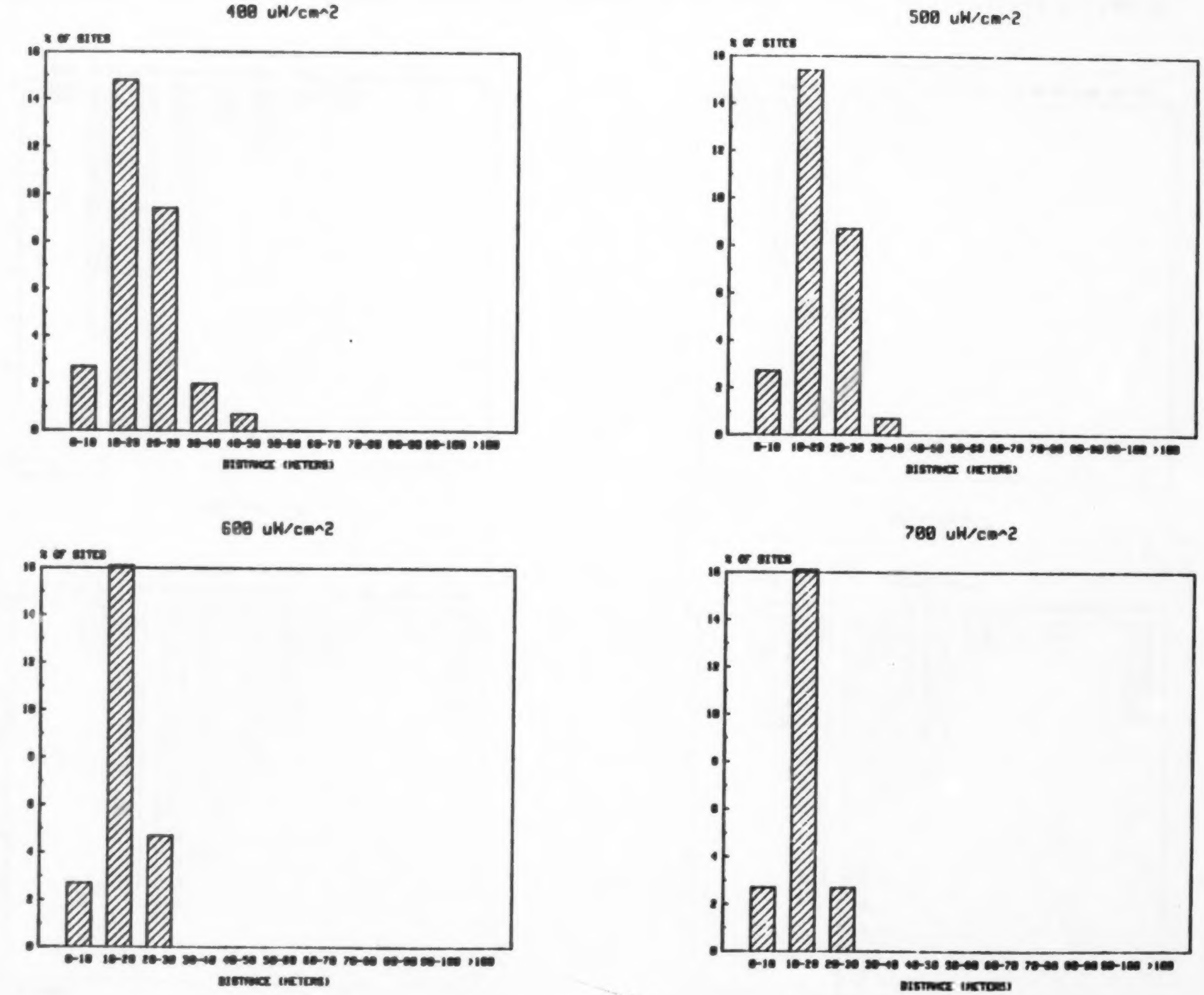


Figure 83. Percentages of MFMG exceeding alternative guidance levels to specified distances.

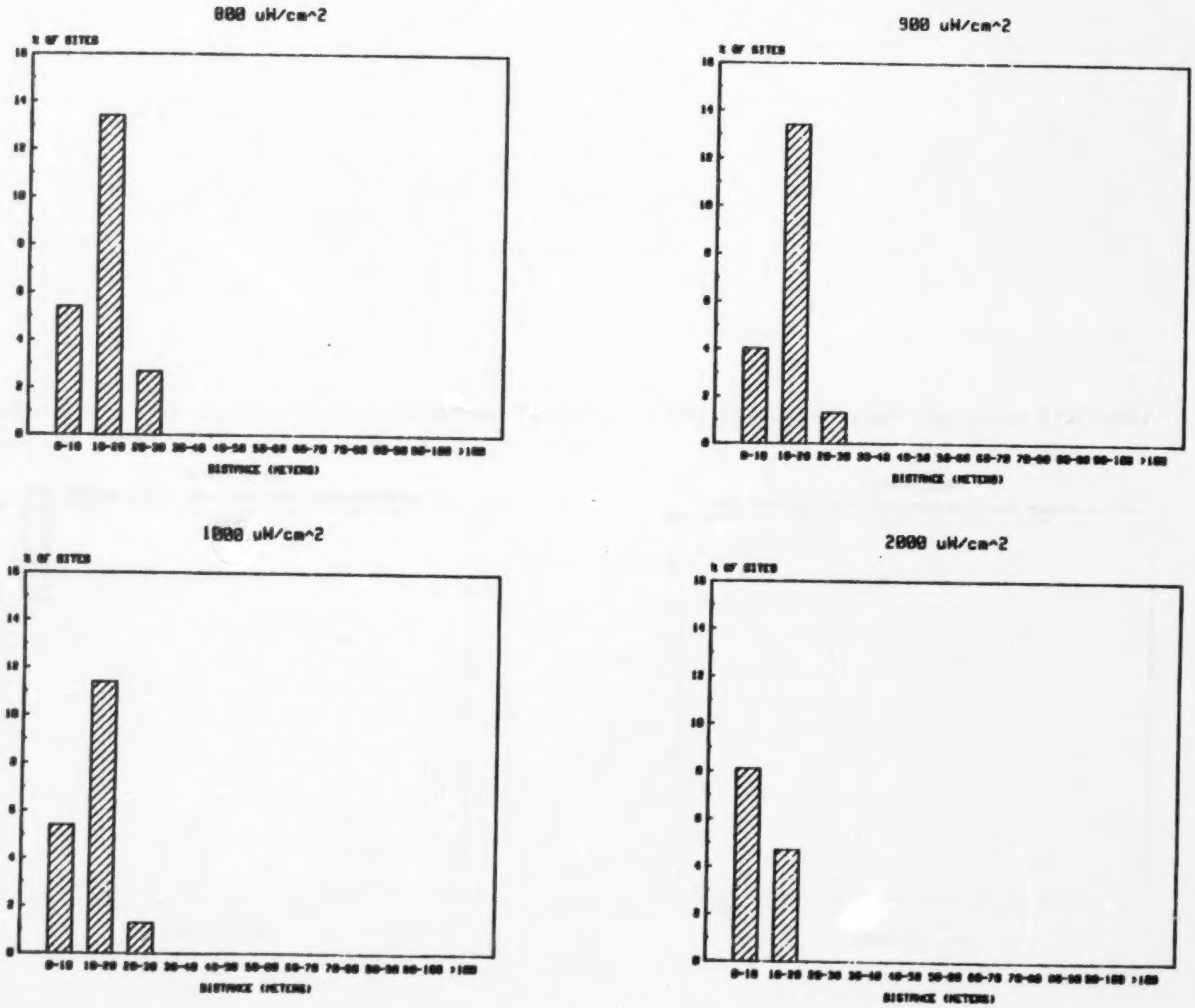


Figure 84. Percentages of MFMG exceeding alternative guidance levels to specified distances.

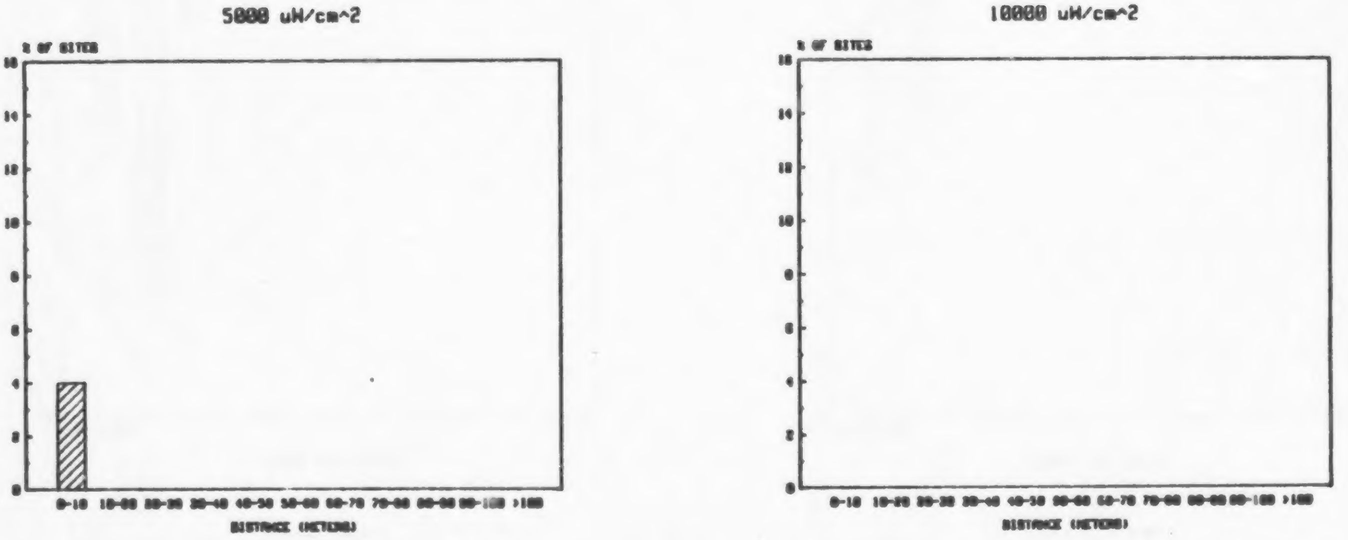


Figure 85. Percentages of MFMG exceeding alternative guidance levels to specified distances.

Appendix F

Preliminary Survey Results

Early in 1984, a survey was conducted to obtain more detailed information about FM broadcast facilities. Since the proposed Guidance level at FM frequencies is not anticipated to be lower than 100 μW/cm^2, the questionnaire was sent only to those stations which the model predicted could exceed this value. Thus the survey results apply most directly to guidance level 6 (100 μW/cm^2) but also provide a source from which information concerning higher guidance alternative levels can be extracted.

Station-by-station analyses are planned which will use the modeling and survey results to determine whether each station has sufficient fencing or property to exclude areas in which it is predicted to exceed the various guidance levels (above guidance level 6). This more detailed application of the modeling results will reduce the impact predicted for the FM service by introducing the less expensive "fix" of fencing or posting the necessary area around the station.

Approximately 52 per cent of the 1,118 questionnaries mailed were returned. Preliminary analyses of the results have been performed which provide a statistical view of certain aspects of FM facilities and nearby land usage. A copy of the questionnaire is shown below.

Question 2 was included to determine the number of potentially impacted stations which are remote from other human activities. Such stations may be required only to post warning signs in order to comply with a given alternative guidance level. It is unknown at this time whether or not posting will be considered a sufficient compliance measure although it does seem to be a reasonable approach for mountaintop and other remote station locations. Table 55 shows the breakdown of responses to this question as of March 28, 1984. Respondents were permitted to check one or two of the descriptions in question 2 so the total responses to this question exceed 100 percent. A prioritizing scheme will be applied to these responses when a more detailed analysis is performed. The table headings are described below:

OMB Clearance No. 2060-0045

EPA QUESTIONNAIRE

------------------------------ Please do not remove this label

----

1. Name and telephone number of person responding to survey:

_______________________ (   ) _______________________.

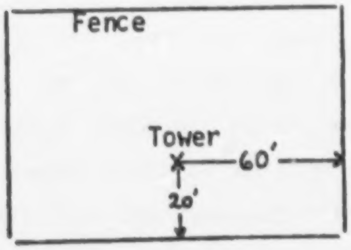
2. Check one or two of the following statements which best describe the location of your transmitter:

   - ☐ Downtown or Urban
   - ☐ Residential or Suburban
   - ☐ Industrial - Commercial
   - ☐ Rural
   - ☐ Remote from other human activities

3. What is the shortest distance, d, between the base of your transmitter tower and the fence surrounding the tower? Write "0" if there is no fence. Approximate this value if site plan is not readily available:

   d = ____________________.

Example:

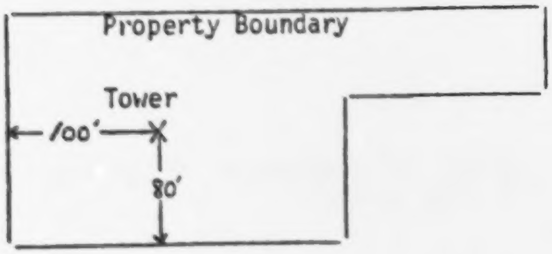


d = 20'

4. What is the shortest distance, r, between your transmitting tower and the boundary of the property owned or leased for operation of your transmitting facility? Approximate this distance if site plan is not readily available:

r = ______________________ .

Example:



r = 80'

5. Is the property boundary fenced?

☐ Yes
☐ No

6. Check the box(es) which best describe your antenna facility:

☐ Only broadcast antenna on tower
☐ Co-located with other broadcast antennas on same tower
☐ On tower located near other transmitting facilities (antenna farm)

7. Do you anticipate an antenna replacement within:

☐ 0-3 years
☐ 3-5 years
☐ 5-10 years
☐ Not anticipated

Answer the following questions only if your antenna is located on top of a building.

8. Is the rooftop accessible to the public? (observation deck, swimming pool, etc.):

   ☐ Yes

   ☐ No

9. Are there any nearby buildings of comparable or greater height? (We define "nearby" as within one city block.):

   ☐ Yes

   ☐ No

10. What is the street address of the building on which your tower is located? Include city, state, and zip code:

    Building: ____________________

    Street Address: ____________________

    City, State, Zip Code: ____________________

Please return this questionnaire to the U.S. Environmental Protection Agency, Attn: Paul Gailey, Office of Radiation Programs, P.O. Box 18416, Las Vegas, NV 89114.

SFMG - Single FM stations on ground-mounted towers

SFMB - Single FM stations on building-mounted towers

MFMG - Multiple FM stations at the same site on ground-mounted tower(s) (questionnaire was sent to only one station at the site)

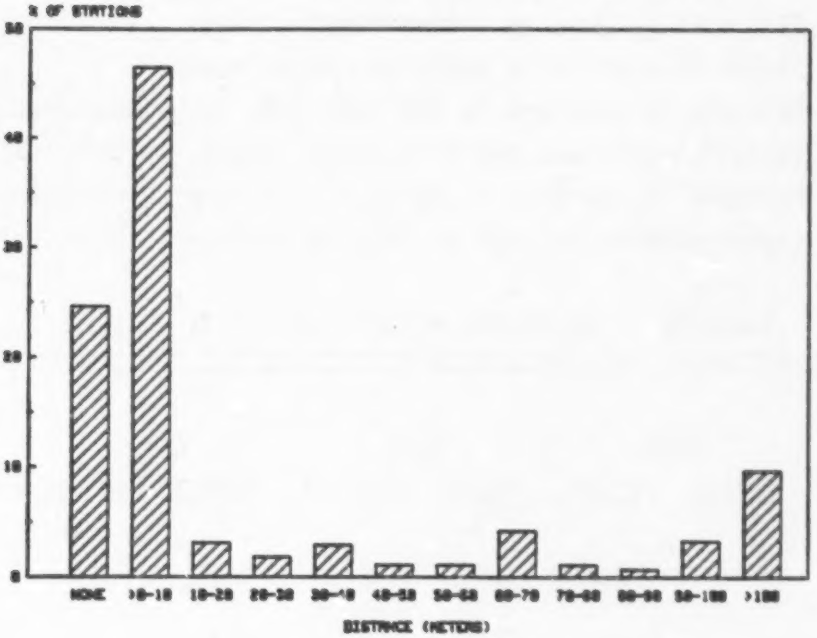
MFMB - Multiple FM stations at the same site on building mounted tower(s) (questionnaire was sent to only one station at the site)

TABLE 55. PRELIMINARY RESULTS FOR SURVEY QUESTION 2

Location of Transmitter	SFMG		SFMB		MFMG		MFMB	
	Number	Percent	Number	Percent	Number	Percent	Number	Percent
Downtown or Urban	37	8.2	44	53.7	4	9.8	7	70
Residential or Suburban	108	23.9	39	47.6	9	22.0	1	10
Industrial - Commercial	45	10.0	4	4.9	4	9.8	2	20
Rural	214	47.3	11	13.4	15	36.6	1	10
Remote	142	31.4	8	9.8	18	43.9	2	20

Question 3 was designed to reveal the number of stations which are already fenced to sufficient distance to prevent exceeding the various alternative guidance levels. The responses were compiled into histograms for SFMG and MFMG for an overview of existing fences (Figure 86). An extention of this analysis could include a comparison of each survey response with the modeling results for that station to determine the number of stations already possessing sufficient fencing. It should be noted that some stations may have one fence close to the tower and another fence at some distance or surrounding the property boundary. Question 5 is intended to help reveal this condition. Responses to question 3 probably refer to the closest fence, so in cases where the answer to question 5 was yes, the response to question 4 was used as the fencing distance. Results shown in Figure 86 can be compared to the modeling

DISTANCE FROM TOWER TO FURTHEST FENCE - SFMG



DISTANCE FROM TOWER TO FURTHEST FENCE - MFMG

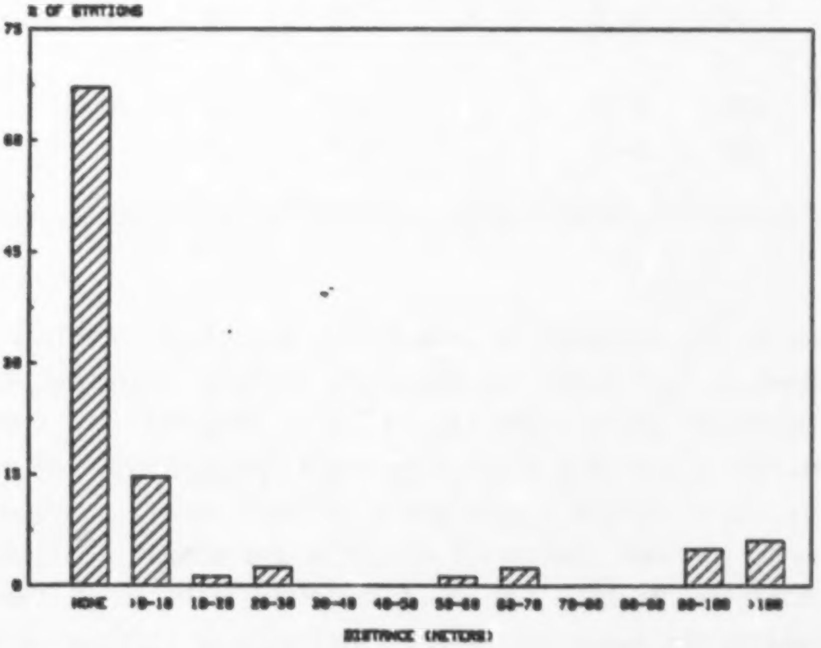


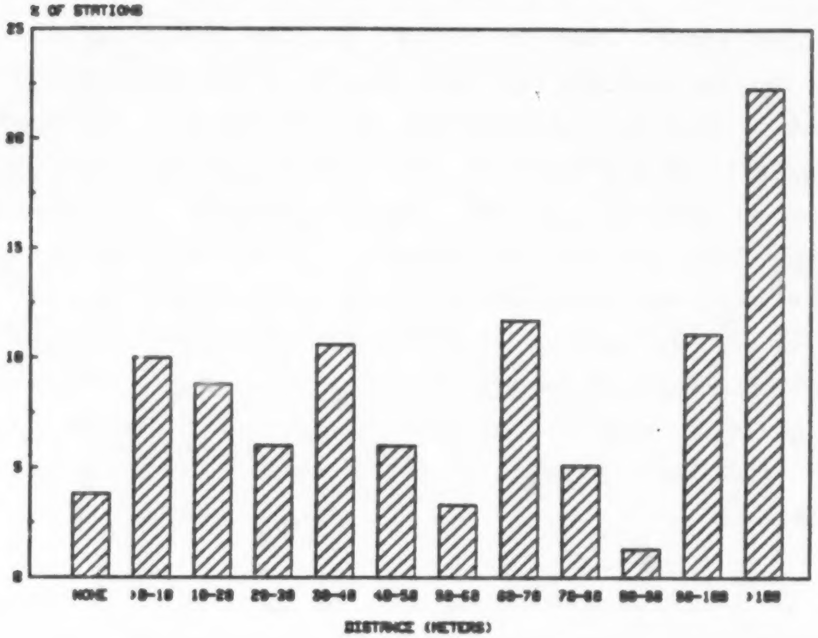
Figure 86. Distribution of distances from FM towers to furthest fence.

results for 100 $\mu W/cm^2$ shown in Figures 77 (for SFMG) and 82 (for MFMG). The modeling results indicate that 96.4 percent of the SFMG stations exceeding 100 $\mu W/cm^2$ do so only at distances less than 50 meters. The survey results, however, show only 20.1 percent of the stations having fences to distances greater than 50 meters. It can thus be roughly estimated that about 20 percent of SFMG stations predicted to exceed 100 $\mu W/cm^2$ are already sufficiently fenced and would not actually be impacted by such a guidance level. Similarly, 90.2 percent of MFMG sites predicted to exceed 100 $\mu W/cm^2$ do so to distances of 70 meters or less. The survey results show only 11 percent of MFMG stations to have fences at distances greater than 70 meters. A reduction in impact of 10 percent or greater might be expected for these stations.

Figure 87 illustrates the responses to question 4 in histogram form. Although the question 3 responses indicate only a modest, yet significant, reduction in impact due to existing fences, the question 4 results reveal that a substantial decrease in predicted impact may occur because of property control. In cases where a station owns or controls sufficient property, erection of a fence to exclude areas exceeding the guidance may be a less expensive "fix." When the final analyses of the survey responses are completed, the results will be sent to Lawrence Livermore National Laboratory for economic analysis. As mentioned previously, 96.4 percent of SFMG stations predicted to exceed 100 $\mu W/cm^2$ do so only to distances of less than 50 meters. The survey results indicate that 54.8 percent of these stations own or control property to distances greater than 50 meters from their tower. Over 30 percent of MFMG sites own or control property to distances greater than 70 meters from their tower. Question 6 was included to identify multiple sites and distinguish between cases where stations are located on the same tower and cases where towers are located close together.

Actual impact of the "antenna fix" mitigation strategy depends partly on the time frame in which a station intends to replace their antenna for reasons other than Federal Guidance. The responses to question 7, as shown in Table 56, give an indication of this time frame.

DISTANCE FROM TOWER TO PROPERTY BOUNDRY - SFMG



DISTANCE FROM TOWER TO PROPERTY BOUNDRY - MFMG

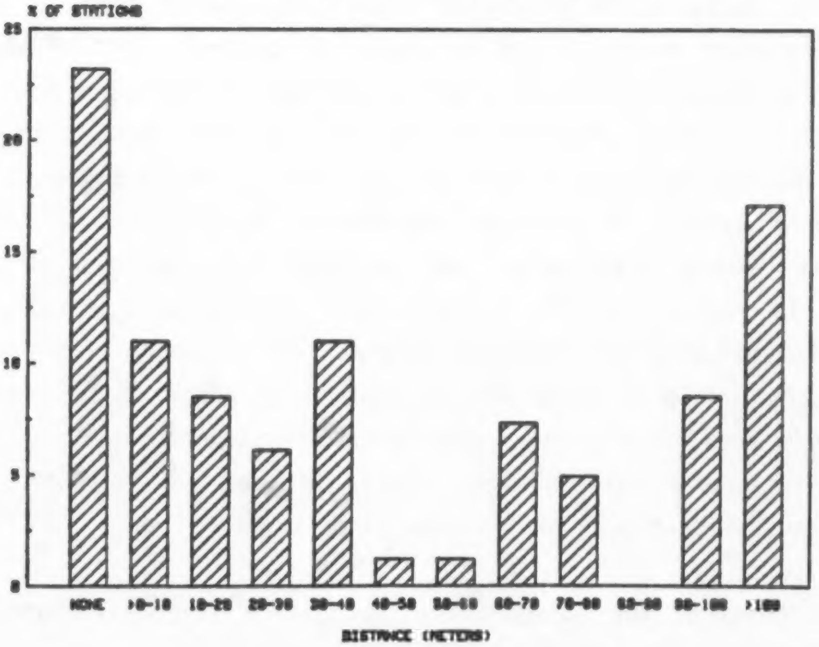


Figure 87. Distribution of distances from tower to property boundary from survey results.

TABLE 56. TIME FRAME FOR ANTICIPATED ANTENNA REPLACEMENT

Time Until Anticipated Antenna Replacement	SFMG Number	SFMG Percent	SFMB Number	SFMB Percent	MFMB Number	MFMB Percent	MFMB Number	MFMB Percent	TOTAL Number	TOTAL Percent
0-3 years	95	20.0	09	23.2	00	26.8	6	60.0	030	22.4
3-5 years	20	4.6	9	00.0	3	7.3	0	00.0	34	5.8
5-00 years	22	4.9	6	7.3	0	2.4	0	0.0	29	5.0
Not anticipated	304	69.5	48	58.5	26	63.4	3	30.0	390	66.8

Questions 8, 9, and 10 relate only to building-mounted stations. Of 76 responses to question 8, 75 indicated that the rooftops on which their towers are mounted are not accessible to the public. Question 9 asks whether or not there are buildings of comparable or greater height within one city block in order to address the problem of beam interception by nearby buildings. Of 76 responses, 30 stations (39.5 percent) indicated that there were nearby buildings of comparable or greater height. Question 10 of the survey provides exact information about the locations of building-mounted stations so that a more detailed analysis of building-mounted stations can be performed in the future.